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Modeling the Effect of Green Infrastructure on Direct Runoff Reduction in Residential Areas

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MODELING THE EFFECT OF GREEN INFRASTRUCTURE ON DIRECT RUNOFF REDUCTION IN RESIDENTIAL AREAS

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ABSTRACT

Urbanization causes a serious impact on storm water systems by expansion of impervious surfaces. Low Impact Development (LID) is a technique growing in popularity to solve the issue of storm water management. However, to evaluate the benefits of LIDs is a difficult task due to realistic parametrization of LIDs and subcatchments for modeling. The goals of this study are: a) to provide a practical guideline to parameterize and simulate LIDs (bio-retention and rain barrels) in residential areas; and b) to evaluate the resulting effect on the current drainage system under various design storms. U.S. Environmental Protection Agency's Storm Water Management Model 5 (SWMM5) was used to simulate the hydrologic performance of LID controls and their effects on reducing direct runoff from a residential area, Klusner Avenue in Parma, Ohio. This study conceptualized the study site in reasonable detail, including house, garage, backyard, tree lawn, driveway, sidewalk, and street, so that the performance of LID controls could be identified easily. Specifically, a street catchment was carefully modeled using an open-conduit routing option, which simulated the street drainage systems more effectively. SWMM5 parameters were calibrated using the observed rainfall-runoff data which was collected before implementing LID practices at Klusner Avenue. The Nash-Sutcliffe efficiency (NSE) had a value of 0.69 for the calibrated model which indicates a strong fit between the output and observed data. Finally, the calibrated model was used to add LID controls to evaluate its effects under various design storms, 1-year, 2-year, 5-year, 10-year, 25-year, and 50-year return periods. The results show that two types of LID controls, bio-retention cell and rain barrel installed in the study site reduced the total runoff volume from 9 to 13% and the peak flow by from 11 to 15% depending on rainfall intensities. The analysis of results suggested that the performance of LID controls should be based on not only their capacity and treatment area but also target design storm and unit cost.

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ACRONYMS

BC	Bio-retention Cell
BMP	Best Management Practice
CSO	Combined Sewer Overflow
EPA	Environmental Protection Agency
ET	Evapotranspiration
GI	Green Infrastructure
GIS	Geographic Information System
IWS	Internal Water Storage
LID	Low Impact Development
MPCA	Minnesota Pollution Control Agency
NEORSD	North East Ohio Regional Sewer District
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
RB	Rain Barrel
SCM	Storm Water Control Measure
SCS	Soil Conservation Service
SWMM	Storm Water Management Model
SWMM5	Storm Water Management Model 5

CHAPTER I

INTRODUCTION

The topic of this thesis is modeling the Low Impact Development (LID) practices at a catchment scale using SWMM5 along with the benefits of LID for residential communities. This thesis clearly explains the parameterization guidelines of LIDs and evaluating its effects on storm water system. Also, the goal of this research is to provide new modeling approaches, alternative to the traditional SWMM5 approach, to better represent the realistic behavior of a LID-controlled subcatchment.

1.1 Background

Urbanization refers to the increase of population living in urban areas. In 1800, only 3% of population lived in urban areas (World population, 2017). Historically, the human population has lived in rural areas and been dependent on agriculture. The world has experienced an unexpected growth of urbanization in recent decades, which has caused the natural landscapes to transform to impervious land covers (World population, 2017).

Impervious land cover occurs when the soil is covered by impermeable materials such as asphalt or concrete. Natural landscapes are shifted to impervious covers due to urbanization.

Impervious cover is a growing environmental concern as the world continues to develop. The impervious areas are responsible for more storm water runoff than any other land use. It alters the hydrologic cycle and affects urban air and water uses. Impervious cover collects particulate matter from the atmosphere, pollutants from vehicles, debris, and many other sources. These pollutants are then transferred through sewer pipes to lakes and rivers thus contaminating them. This contamination led to the installation of combined sewer systems that use a single pipe system to collect and deliver sanitary and storm sewers (Combined Sewer, 2016). This type of collection generates Combined Sewer Overflows (CSO) during high storm events. Increased urbanization led to increased paved areas that channel huge amounts of rain into the combined sewer.

The North East Ohio Regional Sewer District (NEORSD) manages waste water and storm water in Cleveland, Ohio. In 2011, NEORSD filed a “consent decree” with the U.S. EPA (U.S. Environmental Protection Agency) in July 2011, and according to the decree, the NEORSD has twenty-five years by 2036 to reduce CSO volumes by 90% (Jefferson, 2013). Annually, 4.5 billion gallons of untreated sewage is being discharged into Lake Erie (Lyandres, 2012).

Impervious cover and CSO pose a great challenge. They have a profound and irreversible effect on water quality, water quantity, and ground water flow. According to the nonprofit center for Watershed Protection, as much as 65% of the total impervious cover over America’s landscape consists of streets, parking lots, and driveways—what a center staff referred to as “habitat for cars” (Frazer, 2005).

Best Management Practice (BMP) is an alternative approach that protects the natural environment and promotes economic growth. BMP is a structural “thing” that is installed on-the-ground. Storm Water Control Measure (SCM) is another term used for BMP. Green Infrastructure (GI) principles allow the water to permeate into the ground to reduce storm water runoff (USEPA, 2000). GI is the term used for larger planning scope such as inter-jurisdictional communication and planning, and security of steady funding streams. LID focuses on direct treatment of storm water at the site. LIDs goal is to manage storm water with lesser impact on nature. Bio-retention cell facilities, rain barrels, porous pavements, rooftop disconnection, green roofs, and rain gardens are the LID practices that are commonly used in controlling storm water. LID application in these days play an important role because it conserves water and thus balances humankind and nature under expecting climate change.

Residential communities have from 12% to 38% of their areas considered as impervious depending on the lot size (Cronshey, 1986). Communities need to recognize that proper storm water management is a marketable asset to the community. Storm water management supports property values in the community by eliminating flooding concerns and maintaining traffic corridors. The Ohio Supreme Court ruled that NEORSD has the authority to assess a fee for storm water (Maloney, 2015). The storm water fee is based on the amount of impervious surfaces, which include roofs, roads, driveways, and parking lots. It measures the amount of impervious surfaces based on the number of Equivalent Residential Units for non-residential property, and the fee is charged to residential property based on square footage of the impervious surface. The fee ranges from \$3.09 to \$9.27 per month depending on the square feet of the impervious surface (Meyers, 2015).

Storm water fee credits are available to account holders who manage storm water through LID or through activities that reduce the district's cost of providing a regional storm water management program (NEORSD, 2016). Each type of account holder has different types of credits: individual residential property credit, storm water quantity credit, storm water quality credit, and education credit. The credits are about 25 % for individual residential property credit, and up to 75% for storm water quantity credit. The storm water credits require maintenance of control structures to alleviate the fee. The storm water quantity credit is available to applicants who have district-approved SCMs which reduce peak flow and runoff volume flowing from impervious surfaces (NEORSD, 2016). Rain barrels, rain gardens, bio-retention, and vegetative filter strips are effective LIDs that manage storm water for single family residential properties and non-residential properties.

Quantifying the effect of LIDs can be made using Hydrologic-Hydraulic models. Models become important when there is limited data known for a site. U.S. EPA offers a Storm Water Management Model 5 (SWMM5) to simulate runoff quantity and quality (Rossman, 2010). Typically, LID controls such as vegetation swale, rain barrel, infiltration trench, and rain garden have been evaluated at a micro-scale e.g., one or two houses, but little research has been conducted on evaluating their quantitative effects on a drain system at a larger scale such as a community scale.

As the rainfall-runoff processes such as infiltration, overland flow, conduit flow, and groundwater flow are spatially continuous, the effects of LID controls within a catchment should be evaluated in the same scale. By doing so, their performance can be assessed with respect to a nearby major sewer junction. Modeling the LID is essential because direct experimentation may not be feasible due to inaccessible inputs and outputs, time constants that are not compatible with human decisions, and the obstruction of the experiment due to disturbances; however, modeling provides the only way to imagine how LID works.

1.2 Research Questions

The research questions that this thesis examines are as follows.

a. Are the current LID modeling techniques reasonable to simulate a community scale?
b. What are the benefits of modeling LID for the residential communities?
c. What is the role of LID in runoff abatement?
d. Compared to traditional storm water management approach, would LID be effective in preserving storm water?

1.3 Research Objectives

The purpose of this study is to simulate the quantitative effects of LID controls on storm water reduction by suggesting guidelines for using LID controls in SWMM. The main objectives that answer the research questions, therefore, are

a. To simulate and calibrate the model to estimate peak flow and total volume.

b. To provide guidelines how to parameterize popular LID practices using SWMM5.
c. To suggest improved modeling approaches to better represent the hydrologic behavior of a LID-controlled subcatchment.
d. To test the improved LID modeling approaches to a residential catchment in the Cleveland area, OH to evaluate the capacity of the current drainage system under severer storm events.
e. To analyze the changes in hydrologic conditions before and after LID application.

1.4 Literature Review

The hydrologic cycle is a systematic and repetitive process in which water moves from the earth's surface through evaporation to the formation of clouds in the atmosphere and back to earth through precipitation. The earth's hydrologic cycle clearly provides the precipitation, evaporation, and runoff potential of land surface. The hydrologic cycle is disrupted due to transformation of natural landscape to impervious surfaces. This transition from pervious to impervious cover prevents the infiltration of water into soil thus decreasing groundwater recharge. Increased impervious surface is due to increased urban cover.

1.4.1 Urbanization

Through urbanization pervious areas are replaced by impervious areas. For example, forests are replaced with buildings and roads, thus increasing the storm water runoff, peak flow, and time to peak (Booth, 1991; Dietz & Clausen, 2008). Increased urbanization also causes increased pollutant and sediment delivery that contaminates lakes and streams due to the unfiltered and rapid transport of chemicals and nutrients (Wahl et al., 1997). Also, increased pavement area causes a decline in ecosystem functions and aquatic species. Aquatic systems and base flows are impacted at a threshold of 10% to 12% impervious cover (Wang et al., 2001). Global warming and high precipitation events have worsened the impact of urbanization on hydrologic cycle (Arnell & Nigel, 1999). The conventional approach of managing storm water is to collect in gutters and convey it through concrete channels and pipes, carrying it to receiving water bodies such as lakes and ocean thus contaminating lakes (Dietz, 2007).

Due to those negative impacts of urbanization on hydrologic cycle, environmentally efficient and cost effective storm water management practices have been developed to combat the increased surface runoff. Storm water management practices involve controlling the runoff thereby mitigating the adverse impacts caused by the growth of cities and roads. Prince George County, Maryland, implemented an innovative way of handling storm water management practices in the form of LID in the mid-1980s (Coffman, 2000).

1.4.2 Low Impact Development (LID)

Basically, LID is a land re-development approach to manage storm water. The main goal of LID is to reduce the negative effects of precipitation flooding waters by maintaining the pre-development hydrology of a site by decentralizing micro-scale controls (Coffman, 2000; Shafique & Kim, 2015). LID practices effectively reduce water-related problems through infiltration and evaporation of the storm water resulting environmental, social, and economic benefits.

The common LID practices are bio-retention, green roofs, permeable pavements, rain gardens, vegetative swales, and rain cisterns (a.k.a. rain barrel) that are used to create a functionally equivalent hydrologic landscape (Coffman, 2002). These LID practices play an important role because of their ability to store water, allowing it to infiltrate or releasing it to receiving streams. They also have the benefit of lengthening the flow path and runoff time (County, 1999). The two popular LIDs currently used in residential areas are bio-retention cells and rain barrels. An analysis of LID for runoff reduction obtained the benefits of optimized LID implementation in reducing runoff and peak flow rates because LID reduces the need for expensive channel systems such as pipes, channels, and combined sewer systems (NAHB, 2003; Jia et al., 2012).

Bio-retention cell aims to manage storm water close to the source and direct surface runoff into a vegetative zone where water infiltrates into native soil thus increasing the groundwater. Bio-retention cells, the most widely applied LID in U.S., are landscaped depressions that allow percolation through the soil and storage layer, thereby removing contaminants through infiltration (Davis et al., 2009). Properly designed bio-retention removes pollutant compounds that consists of heavy metals. Many studies have shown that bio-retention cells provide significant mitigation of water quality issues through the reducing nutrient and suspended solid concentrations (Roy-Poirer et al., 2010). Davis (2008) observed that bio-retention can reduce the peak flow from 44% to 66% depending on site conditions such as soil and basin slope with substantially delayed time-to-peak. Based on Davis (2008) analysis, bio-retention captured about 18% of the total inflow volume for 49 rainfall events.

Roof runoff usually leads to contamination of storm water with heavy metals. Research on roof runoff shows that it has high levels of zinc, lead, polycyclic aromatic hydrocarbons and pathogens (Clark et al., 2008). These metals are dangerous to human health when exceeding the maximum recommended concentrations in irrigation water e.g. zinc has 2 mg/L as recommended maximum concentration (Clark et al., 2008). The most efficient way to treat roof runoff impurities is through LID practices such as rain barrels. The case study by Jennings et al. (2013) in Cleveland Heights, Ohio presented that a 189-L rain barrel connected to 25% of a 186-m^2 residential roof could serve a 14-m^2 garden and reduce the total roof growing-season runoff by 2.4% to 5.4% and the total annual roof runoff by 1.4% to 3.1%, depending on the irrigation strategy applied. Rain barrels are effective to treat households' impact on local waterways while helping to reduce water bills by collecting gallons of free irrigation water year around.

LID practices are widely established all over the United States, and many agencies in cities have adopted LID to retrofit urban development (USEPA, 2000). The literature on the effect of LID in mitigating the runoff for urban residential areas is of great importance. Despite many results shown on the effective performance of LID, there is still a need to measure the quantitative effects of LID on the watershed hydrologic cycle. Recently, Jarden et al. (2015) analyzed the changes in storm water runoff in the West Creek Watershed, OH. They measured practically the rainfall-runoff events in a catchment (Parma, OH) before and after implementing LID controls, and found that LID control can reduce storm runoff up to 50% in a smaller lot. With effective management of total runoff volume and peak flow, storm water fees are credited to reduce by up to 50%. By improving understanding of LID performance, storm water management decisions become more viable and thus expecting the reduced risk of future harmful impacts (Pyke et al, 2011).

1.4.3 Modeling and SWMM

A realistic modeling approach is needed to more accurately predict storm water runoff from a catchment as LIDs become more ubiquitous. When considering future climate change e.g., typically stronger rainfall intensity than the design standard, the models become more useful to watershed if the model can provide future runoff predictions. Several analyses of hydrologic and hydraulic models have identified that SWMM is a comprehensive and representative rainfall runoff model (Tsihrintzis and Hamid, 1997).

SWMM was originally developed by EPA in the early 1970s and is capable of modeling the transport of runoff and the pollutant loads (Rossman, 2010). SWMM is used for single-event or long-term simulation of runoff quantity and quality, primarily from urban areas. The recent version of SWMM (SWMM5) has been extended to model LID controls to show its effect on runoff mitigation (Rossman, 2010; McCutcheon, 2013). SWMM5 LID controls include bio-retention, rain gardens, rain barrels and others. SWMM5 also takes climatic data into account to estimate snow melt and evaporation rates. The climatic data are air temperature and study area location.

However, few studies have been identified to show the comparison between simulated flow and observed flow from an LID watershed. Tsihrintzis and Hamid (1997) presented the calibrated SWMM models were accurate enough to predict storm water runoff of a watershed under various conditions. Jang et al. (2007) verified that an uncalibrated SWMM5 model found a close match to observed data when the parameters are properly estimated. In most of the studies, urban watersheds are modeled using lumped subcatchments which simplifies the amount of input data. Lumped models adjust the variables to represent the geometry of the study area (Tan et al., 2008). The geometry of the study area requires detailed design and analysis of LID prior to its implementation. When combination of LID controls were modeled, simplification of model poses a great challenge. Typically, LID controls such as vegetation swale, rain barrel, infiltration trench, and rain garden have been evaluated at a micro-scale like one or two houses, but little research has been conducted on evaluating their quantitative effects on a drain system at a larger scale like a community scale (Aad et al., 2010). Moreover, the interaction between surface flow and storm sewer flow is not accounted in previous studies. Hence, detailed modeling of catchments and flow interactions is necessary to study the realistic performance of the study areas.

1.5 Organization of the Thesis

Chapter 1 introduced the topic of the thesis and defines the research questions, and research objectives. Literature review is included to show the effects of LID practices and the previous studies done on modeling related to this thesis topic. Chapter 2 provides the site description and data collection. Chapter 3 provides the methodology of modeling bio-retention and rain barrel in SWMM5 at a catchment level. Chapter 4 discusses the results of the simulations and offers recommendations for improvements. Chapter 5 finally provides the summary and conclusions.

CHAPTER II

STUDY AREA AND DATA

In this chapter, study site characteristics and data sources are explained. The research site chosen is Klusner Avenue, Parma, Ohio because this area maintains observed rainfall-runoff events before and after LID development in the Cleveland area. These data are essential to calibrate the model to simulate the effects of LIDs on runoff.

2.1 Site Description

The research site is located near the West Creek Watershed in Parma, Ohio (Figure 1(a)). The West Creek watershed is a sub watershed along the Cuyahoga River which drains an area of 36 km^2. West Creek drains the cities of Parma, Seven Hills, Brooklyn Heights, Independence, and portions of North Royalton and Broadview Heights before emptying into the Cuyahoga River (NEORSD, 2017).

The West Creek Ecosystem Restoration Project is a green infrastructure project implemented in 2013 at the current study site (Jarden et al., 2015). The study site includes three types of LID controls: 1) rain gardens installed in the front and back yards; 2) bio-retention cells implemented in the tree lawn areas along with street as shown in Figure 1(b); and 3) rain barrels used to collect runoff from the roof houses and garages and release it to backyards as shown in Figure 1(c).

The research site has the Mahoning-Urban land complex, undulating soil type, which is a poorly drained soil (USDA [United States Department of Agriculture], 2016). The research site, with high impervious surfaces and poorly drained soil, leads to high storm water runoff and low infiltration capacity. The study site, Klusner Avenue, is classified as the class C or class D hydrologic soil group predominantly of poorly drained soil. The area has well contoured with an extensive storm drainage system. These factors led to low infiltration rates with high runoff rates. The study site with a drainage area of 11.87 ha (about 29.3 acre or 0.12 km^2) includes 174 residential houses with impervious area of about 50%. It has 16 bio-retention cells (Figure 1 (a) and (b)), 37 rain barrels, and seven rain gardens implemented (Jarden et al., 2015).

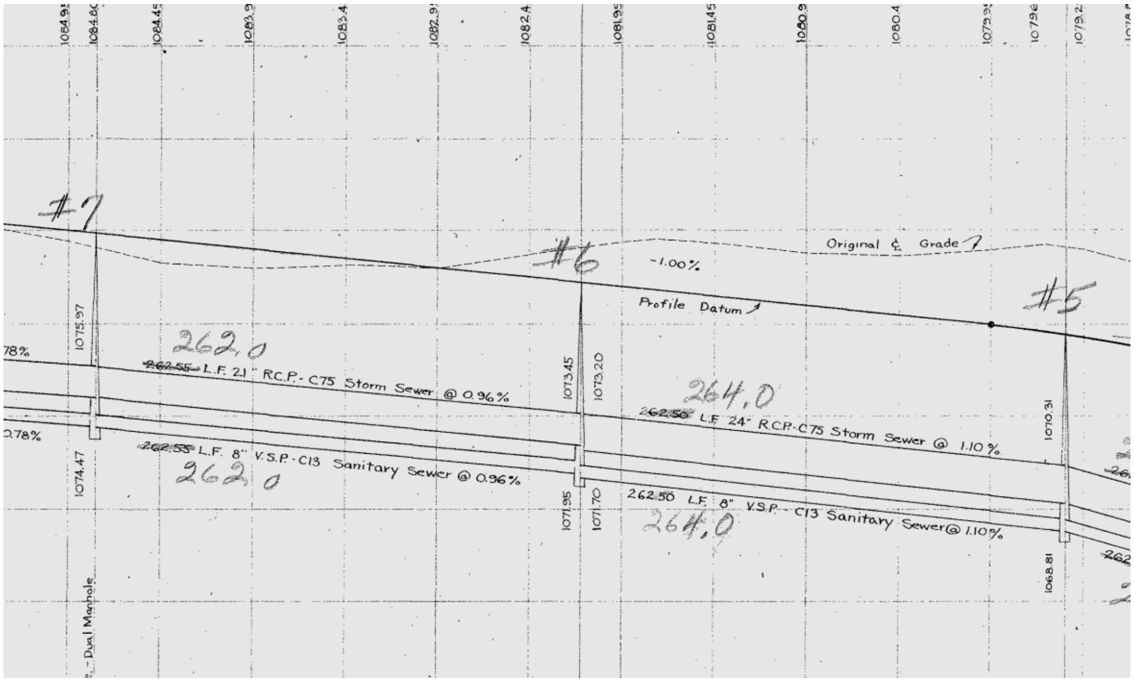
Based on the field trip in March 2016, it was determined that the effect of rain gardens is offset by lawn yards and the exact locations of rain barrel are not identifiable as homeowners' permission is needed. But, from Jarden (2015), rain barrels are placed at the houses where bio-retentions are placed. However, the latter fact does not affect the modeling result because the rain barrels will drain directly to backyards without flow routing.

Figure 1. Study Site Description: (a) The Location of Klusner Avenue in Parma, Ohio, (b) An Example of Bio-retention Cell, and (c) The Outfall of the Catchment

2.2 Data Sources

Observed rainfall or runoff data for the study site is very limited due to the remoteness of rainfall and stream gage. This study extracted the observed hydrologic data from Jarden (2015) for Klusner Avenue measured in 2012. This observed data measured in 2012 was used for SWMM parameter calibration. The rainfall depth for different return periods is taken from U.S. National Weather Service (NWS, 2014). Analysis is made for 1-hr rainfall duration with different return periods.

The subcatchment properties, junction properties, and conduit properties are calculated using the street drawings shown on Figure 2, provided by NEORSD (R. Stoerkel, personal communication, February 9, 2016). Invert elevations, manhole diameters, offset heights for conduits are shown on Figure 2(a), provided by NEORSD (R. Stoerkel, personal communication, February 9, 2016). The percentage of impervious area and area of the subcatchment are calculated using Cuyahoga County Geographic Information System (GIS) as shown on Figure 2(b) (Cuyahoga County GIS, 2016). The properties of bio-retention cell in the study site were measured from the field trip and rain barrel's properties were taken from most general commercial product (see chapter 3 for values). Standard sandy soil properties of bio-retention cell are chosen for its design (Rossman and Huber, 2016). All properties were converted as parameters for SWMM5 and its values are given in chapter 3.



(a)

(b)

Figure 2. Example of Extracting SWMM5 Parameters: (a) Original Junction Drawing and (b) Cuyahoga County GIS System to Estimate Catchment Properties of Klusner Avenue

CHAPTER III

STORM WATER RUNOFF SIMULATION

In this chapter, a detailed description is provided about the SWMM and modeling of LID controls in SWMM. Details about the study site modeling, simulation scenarios and parameters that are used for calibration are included.

3.1 Storm Water Management Model (SWMM)

The U.S. Environmental Protection Agency's SWMM5 is a dynamic rainfall-runoff simulation model used for single-event or long-term continuous simulation of runoff quantity and quality from primarily urban areas. The SWMM software was developed in 1969-1971 and is widely applied to analyze the water quantity and quality in storm water runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas as well as in non-urban areas (Rossman, 2010). SWMM5 is the current version used in this study.

The SWMM5 runoff component operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The principal input parameters for subcatchment are infiltration method, assigned rain gage, outlet node, assigned land uses, surface area, imperviousness, slope, characteristic width of overland flow path, Manning's n for overland flow path on pervious and impervious areas, depression storage in both pervious and impervious areas, and the percent of impervious areas with no depression storage (Rosmann, 2010) (Table 1).

Table 1. Subcatchment Characteristics as Defined in SWMM5

Characteristics	**Description**
Rain Gages	Refers to the rain gage where the rain intensity is defined over a time interval
Outlet	Defines which node or subcatchment is receiving the flow
Area	Area of the subcatchment including any LID controls
Width	Characteristic width of the overland flow path for sheet flow runoff from non-LID area only.
% Slope	Average percent slope of the subcatchment
% Impervious	Percent of the land area which is impervious
n-Impervious	Manning's n for overland flow over the impervious portion of the subcatchment
n-Pervious	Manning's n for overland flow over the previous portion of the subcatchment
D Store Impervious	Depth of the depression storage on the impervious portion of the subcatchment
D Store-Pervious	Depth of the depression storage on the pervious portion of the subcatchment
% Zero-Imp	Percent of the impervious area with no depression storage
Subarea Routing	Choice of internal routing of flow between pervious and impervious sub-areas (allows directing the flow between the pervious and impervious areas within a subcatchment)
% Routed	Percent of the diverted flow toward a sub-area within subcatchment
LID Controls	This is used to edit the use of Low Impact Development controls in the subcatchment

These subcatchment objects represent a land area that receive precipitation and produce runoff to an outlet node. SWMM5 uses the Curve Number method, Horton's method, and the Green-Ampt method for infiltration computation (Rossmann, 2010). Curve Number method is adopted from Natural Resources Conservation Service (NRCS) Soil Conservation Service (SCS) Curve Number method to estimate runoff. The infiltration capacity of a soil can be found from tabulated soil Curve Number. Curve Number and the time takes to completely dry the saturated soil are the input parameters for Curve Number method. Horton's method uses empirical observations showing that infiltration decreases exponentially from an initial maximum rate to some minimum rate over the course of a long rainfall event. The maximum and minimum infiltration rates, a decay coefficient, and time takes to dry the saturated soil are the input parameters for Horton's method. Green-Ampt method assumes that a sharp wetting front exists in the soil column, separating soil with some initial moisture content below from saturated soil above. Initial moisture deficit, soil's hydraulic conductivity, and suction head are the input parameters for Green-Ampt method.

SWMM5 tracks the water quantity using a nonlinear reservoir concept to generate the overland flow. This nonlinear reservoir method solves a continuity equation coupled with Manning's equation based on rainfall excess (Huber, 2003). Surface runoff conceptual view as shown in Figure 3. Surface runoff flow rate, q per surface area of the subcatchment is given as

$$q = \frac{1.49\mathrm{W}\, S^{1/2}(d-d_s)^{5/3}}{An} \tag{1}$$

where

W is a width [L],

S is an average slope of the subcatchment [L/L],

n is a surface roughness coefficient,

A is a surface area of the subcatchment [L^2],

d_s is a depression storage [L], and

d is a ponded rain water atop the subcatchment surface to a certain depth[L].

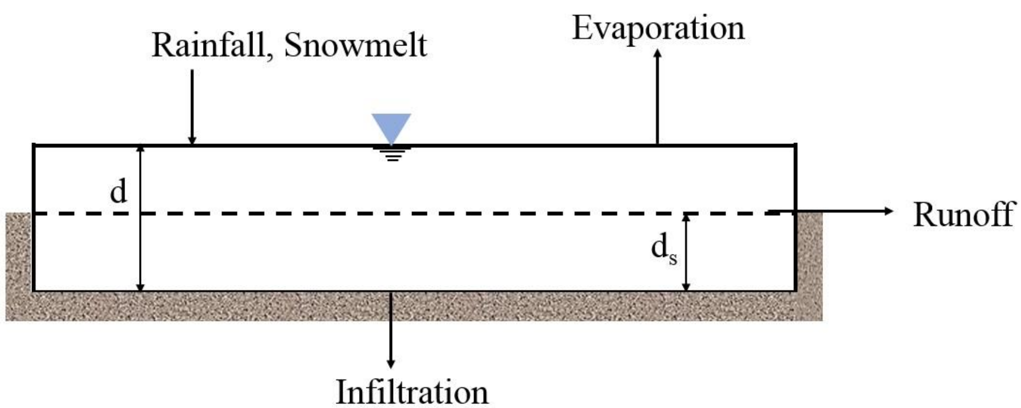


Figure 3. Nonlinear Reservoir Model of a Subcatchment

Steady-flow routing, kinematic wave routing, and dynamic wave routing are the three options for routing component in SWMM5. The inflow to the conduit is translated to the downstream end by one of the options. Steady-flow routing assumes that within each computational time step flow is uniform and steady. Kinematic wave routing allows flow and area to vary spatially and temporally within a conduit. The outflow hydrograph is delayed as inflow through the conduit varies. Dynamic wave routing produces accurate results as it uses complete one-dimensional Saint Venant flow equations. Therefore, this study used the dynamic wave routing method to consider all possible hydraulic conditions e.g., backwater and pressurized surcharge in conduits and junctions (manholes) accurately.

SWMM5 has input file named as [*.inp] file. The [*.inp] file is the schematic representation of the model in SWMM5 and also can be opened with notepad where properties can be edited or duplicated. SWMM5 is also used to model the hydrologic performance of specific types of LID controls.

3.2 Low Impact Development (LID) Controls

There are 7 typical LID controls that can be modeled in SWMM. The LID practices that are included in SWMM5 are bio-retention, permeable pavement, rain garden, rain barrel, infiltration trench, rooftop disconnection, vegetative swale, and green roofs. Each LID in SWMM5 has a variety of process layers such as: surface, soil, storage, and drain. Each subcatchment can have multiple LID controls as shown in Figure 4 (USEPA, 2000). This study explains the modeling techniques of bio-retention cell and rain barrel. Bio-retention cell in residential communities is used to treat runoff from roads whereas rain barrel is used to treat rooftop runoff.

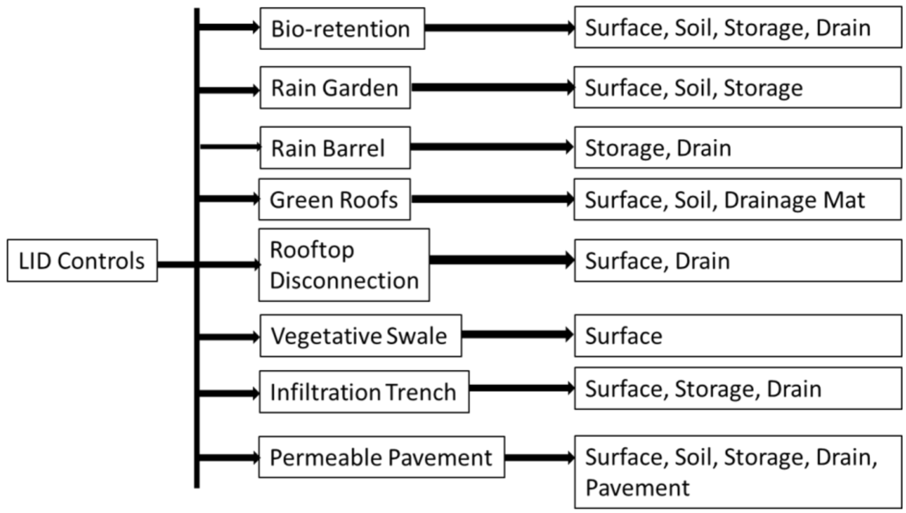


Figure 4. Different Types of LID Controls in SWMM and its Process Layers

3.2.1 Bio-retention Cell

Bio-retention cell is the most widely applied LID practice throughout the U.S., which restores the natural system function by using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source (Davis et al., 2009). Bio-retention cell consists of a grass buffer strip, a sand bed, a pond area, an organic layer of mulch, planting soil, and plants. Runoff water passes across the length of the pond area which consists of organic mulch. Later, water infiltrates into planting soil and sand beds (USEPA, 2000). Some of the bio-retention facilities have underdrains which convey the excess water to the storm drain system.

Internal Water Storage (IWS) layer is also a design type of bio-retention cell included in the subsurface portion of the media which provides water storage volume in the bio-retention. IWS also accounts for pollutant reduction. This study didn’t design for IWS as (Jarden et al., 2015) experimented with traditional bio-retention cell in the study site. But usually, bio-retention cell with IWS layer showed greater reduction in volume than other type of bio-retention cells (Winston, 2016).

The general components of bio-retention cell are surface layer, soil layer, storage layer, underdrain, and overflow structure. A bio-retention cell can be designed with and without underdrains.

Bio-retention in SWMM5

A bio-retention cell is represented in SWMM5 by four vertical layers and each layer is parameterized using a LID control editor shown in Figure 5.

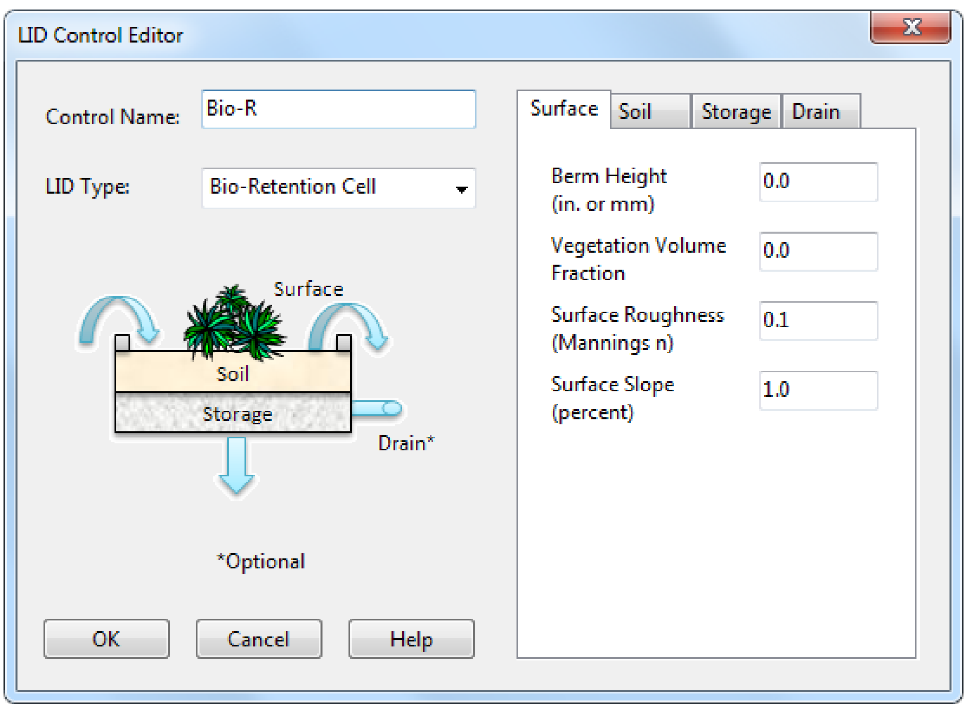


Figure 5. LID Control Editor in SWMM5 (Example of Bio-retention Cell)

The surface layer represents the top vegetative growth in bio-retention cell and it receives rainfall and runoff from surrounding soil. The water from the surface layer is infiltrated into the soil layer or is lost through evaporation. The soil layer contains a soil mix to support the top vegetative growth. This layer receives water through infiltration from surface layer and loses water through percolation to the storage layer below it. The storage layer consists of a stone aggregate. This layer receives water from the soil above it, and loses water through infiltration to natural soil or by an underdrain pipe (Rossman and Huber, 2016). The following hydrologic assumptions were made for bio-retention cell simulation in SWMM5.

- One-dimensional flow through the bio-retention cell in the vertical direction.
- The soil layer has the moisture content uniformly distributed.
- The flow into the bio-retention cell is evenly distributed across the top surface.
- The cross-sectional area of the bio-retention cell is volume of the bio-retention cell divided by depth of the bio-retention cell and is constant throughout the depth.
- Bio-retention cell acts as a simple reservoir that stores water from the bottom up.

The continuity equation is used to model a bio-retention cell (or similar LID controls). Each continuity equation is the difference between inflow and outflow water flux rates that is described as the change in water content in a layer over time (Rossman and Huber, 2016). The equations used are

$$\emptyset_1 \frac{\partial d_1}{\partial t} = i + q_0 - e_1 - f_1 - q_1 \qquad \text{for a surface layer} \qquad (2)$$

$$D_2 \frac{\partial \theta_2}{\partial t} = f_1 - e_2 - f_2 \qquad \text{for a soil layer} \qquad (3)$$

$$\emptyset_3 \frac{\partial d_3}{\partial t} = f_2 - e_3 - f_3 - q_3 \qquad \text{for a storage layer} \qquad (4)$$

where

d_1 is a depth of water stored on the surface [L],

θ_2 is a soil layer moisture content (volume of water / total volume of soil),

d_3 is a depth of water in the storage layer [L],

i is a precipitation rate falling directly on the surface layer [L/T],

q_0 is a inflow to the surface layer from runoff captured from other areas [L/T],

q_1 is a surface layer runoff or overflow rate [L/T],

q_3 is a storage layer underdrain outflow rate [L/T],

e_1 is a surface evapotranspiration (ET) rate [L/T],

e_2 is a soil layer ET rate [L/T],

e_3 is a storage layer ET rate [L/T],

f_1 is a infiltration rate of surface water into the soil layer [L/T],

f_2 is a percolation rate of water through the soil layer into the storage layer [L/T],

f_3 is a exfiltration rate of water from the storage layer into native soil [L/T],

$\emptyset_1$ is a void fraction of any surface volume (the fraction of freeboard above the surface),

$\emptyset_3$ is a void fraction of the storage layer (void volume / total volume), and

D_2 is a thickness of the soil layer [L].

Hydrologic components involved in bio-retention cell are briefly described by surface inflow, surface infiltration, soil percolation, evapotranspiration, bottom exfiltration and underdrain flow. Surface inflow (i+q_0) is due to precipitation (i) and runoff from surrounding areas captured by bio-retention cell (q_0). Surface Infiltration (f_1) rate into the soil layer was modeled using Green-Ampt equation. The Green-Ampt equation applies after soil is saturated at the top of the soil zone. The infiltration rate in a LID unit is different from that occurred in a subcatchment because the LID unit is comprised of different soil mix or is mostly built to store water for a long time. Soil Percolation rate (f_2) of percolation of water through soil layer into the storage layer was modeled using the Darcy's law. Bottom Exfiltration rate (f_3) is the exfiltration of the storage layer into the native soil. This exfiltration rate would depend on the stored water depth and native soil moisture profile. Underdrain (q_3) is necessary for heavy rainfall events or for clayey soils so that water will not overflow the LID unit. Underdrain delays the time to peak during heavy storms. The outflow from a underdrain pipe is considered as an orifice type outlet using

$$q = CH^n \tag{5}$$

where

C is a drain coefficient

n is a drain exponent

H is a height of the saturated media above the drain.

The various cases for setting LID underdrain parameters are summarized as follows.

- If a storage layer has no drain, then set $C = 0$.
- If a storage layer has an impermeable bottom then set drain with $H = 0$ or to allow the full storage volume to fill before draining occurs, set H = the height of the storage layer.
- If an underdrain carry the flow entering the storage layer up to some specific limit, then set the drain coefficient to the limit and $n = 0$.
- If an underdrain has slotted pipes as an orifice, then set $n = 0.5$ and

C = 60,000 *(total slot area/ LID area).

- If water is to be drained in a specific amount of time T through a diameter D, then $n = 0.5$ and $C = \frac{2\,D^{1/2}}{T}$.

The most common design of a bio-retention cell was compared with its conceptualization in SWMM5 as shown in Figure 6. It is noted that the overflow pipe connected to the underdrain cannot be simulated using the SWMM5 LID controls because it was not considered in SWMM5 LIDs. However, if bio-retention cell is modeled hydraulically, overflow pipe can be modeled using other SWMM5 modules like weir or orifice. Table 2 explains the parameters represented in SWMM5, compared with the on-site bio-retention cell as shown in Figure 6.

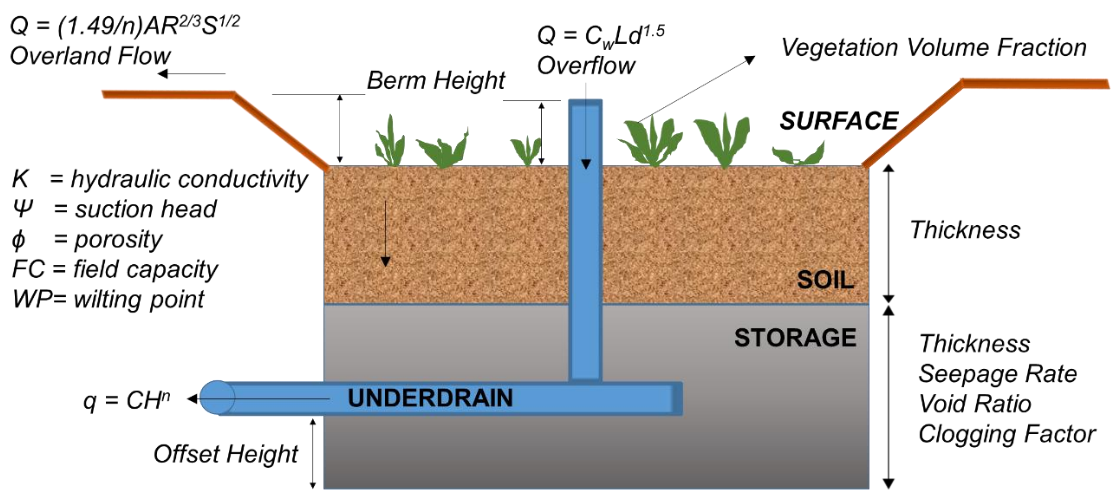


Figure 6. Parameterization of On-site Bio-retention Cell for SWMM5

Table 2. Bio-retention cell Parameters Represented in SWMM5

Layer	Parameters	Description
Surface	Berm Height (in or mm)	Height of the surface layer or overflow pipe from the surface bottom
	Vegetation Volume Fraction	Volume filled with vegetation in surface layer
	Surface Roughness (Manning's n)	n for surface land
	Surface Slope (Percent)	Slope of surface
Soil	Thickness (in or mm)	Thickness of soil layer
	Porosity (Volume Fraction)	Volume of soil voids relative to total soil volume
	Field Capacity (Volume Fraction)	Pour water volume relative to total volume of soil after water from soil is drained fully
	Wilting Point (Volume Fraction)	Volume of pore water relative to well dried soil
	Conductivity (in/hr or mm/hr)	Hydraulic conductivity of soil
	Conductivity Slope	Rate at which hydraulic conductivity decreases with decreasing moisture content
	Suction Head (in or mm)	Soil capillary suction
Storage	Thickness (in or mm)	Thickness of storage
	Void Ratio (Voids/Solids)	Volume of voids with respect to volume of solids
	Seepage Rate (in/hr or mm/hr)	Infiltration rate into native soil
	Clogging Factor	Total volume of runoff treated which clogs the layer bottom/void volume of the layer
Drain	Flow Coefficient	Determines the rate of flow through a drain
	Flow Exponent	Determines the rate of flow through a drain
	Offset Height (in or mm)	Height of the drain line above the bottom of the storage layer

Depending on its design components listed in Table 2 and the examples bio-retention cell design presented in Minnesota Pollution Control Agency (MPCA, 2015), this study suggested that on-site bio-retention cells can be broadly categorized into four cases as follows.

- Case 1. Bio-retention cell with no underdrain

This type of bio-retention cell is suitable for areas where groundwater recharge is possible. The in-situ soils need to have higher infiltration rates to accommodate the inflow from bio-retention.

- Case 2. Bio-retention cell with an underdrain at the bottom

This is designed with an underdrain at the bottom of the storage layer to ensure drainage. This practice doesn't have impervious line and it allows partial recharge. This practice is suitable for all types of soil groups.

- Case 3. Bio-retention cell with an elevated underdrain

This type of bio-retention practice has an underdrain raised to provide a storage area below the invert of the underdrain pipe. The storage area used is equal to the void space of the material used.

- Case 4. Bio-retention cell with an impermeable liner

This type of bio-retention practice has an impervious liner designed to eliminate the chances of groundwater contamination. This practice treats the water through filtration process that occurs when water flows through soil layer. In case of accidental spill, the underdrain can be blocked.

From a modeling standpoint, those four types of bio-retention design can be evaluated for SWMM5 application as presented in Table 3. The bio-retention parameters of SWMM5 were identified as X marks for the cases categorized earlier. Table 3 is useful for a practitioner to determine which type of bio-retention can be modeled using SWMM5 LID controls.

Table 3. Bio-retention Parameters to be Considered for Different Designs

Layer	Parameters	Case 1	Case 2	Case 3	Case 4
Surface	Berm Height	X	X	X	X
	Vegetation Volume	X	X	X	X
	Surface Roughness	X	X	X	X
	Surface Slope	X	X	X	X
Soil	Thickness	X	X	X	X
	Porosity	X	X	X	X
	Field Capacity	X	X	X	X
	Wilting Point	X	X	X	X
	Conductivity	X	X	X	X
	Conductivity Slope	X	X	X	X
	Suction Head	X	X	X	X
Storage	Thickness	X	X	X	X
	Void Ratio	X	X	X	X
	Seepage Rate	X	X	X	
	Clogging Factor	X	X	X	X
Drain	Flow Coefficient		X	X	X
	Offset Height			X	X

Note: “X” marked parameters are considered in SWMM5.

3.2.2 Rain Barrel

Rain barrels collect and stores runoff from rooftops. These are low-cost water conservation devices used to divert runoff from storm sewer systems to backyards. Two types of rain barrels are commonly used in residential areas (Abi Aad et al., 2010). The first type is the overflowing rain barrel in which inflow flows through the downspout connected to rooftop, while outflow flows as the overflow. The overflow is then routed to pervious area such as lawn yards. The second type is the continuously draining rain barrel. The inflow is from the downspout connected to rooftop whereas the outflow is from the outlet drain pipe only as shown on Figure 7. There is no overflow in this case. The water from outlet pipe is routed to a pervious area.

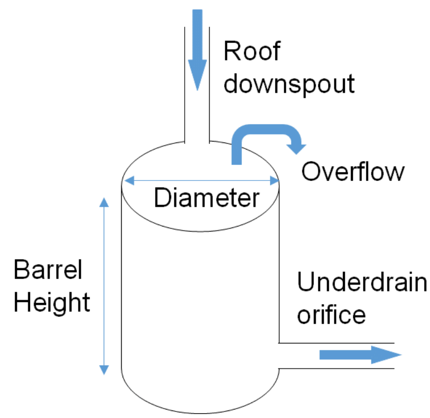


Figure 7. Parameterization of On-site Rain Barrel for SWMM5

Rain Barrel in SWMM5

A rain barrel is represented in SWMM5 by a barrel height with an optional drain pipe as shown on Figure 8. It is modeled just as a storage layer with all void space. It has the drain valve placed above an impermeable bottom. The continuity equation used for computing a rain barrel is given as

$$\frac{\partial d_3}{\partial t} = f_1 - q_1 - q_3 \tag{6}$$

where

q_3 is a rain barrel drain flow [L/T],

q_1 is a surface layer runoff or overflow rate [L/T],

d_3 is a depth of water in the storage layer [L], and

f_1 is a represents the amount of inflow captured by the rain barrel [L/T].

The underdrain equation used in a rain barrel is like that of bio-retention. If the orifice equation is used, the drain coefficient $C = 0.6\ (\frac{\text{Area of drain valve opening}}{\text{Surface area of the barrel}})\sqrt{2g}$ and the drain exponent n = 0.5.

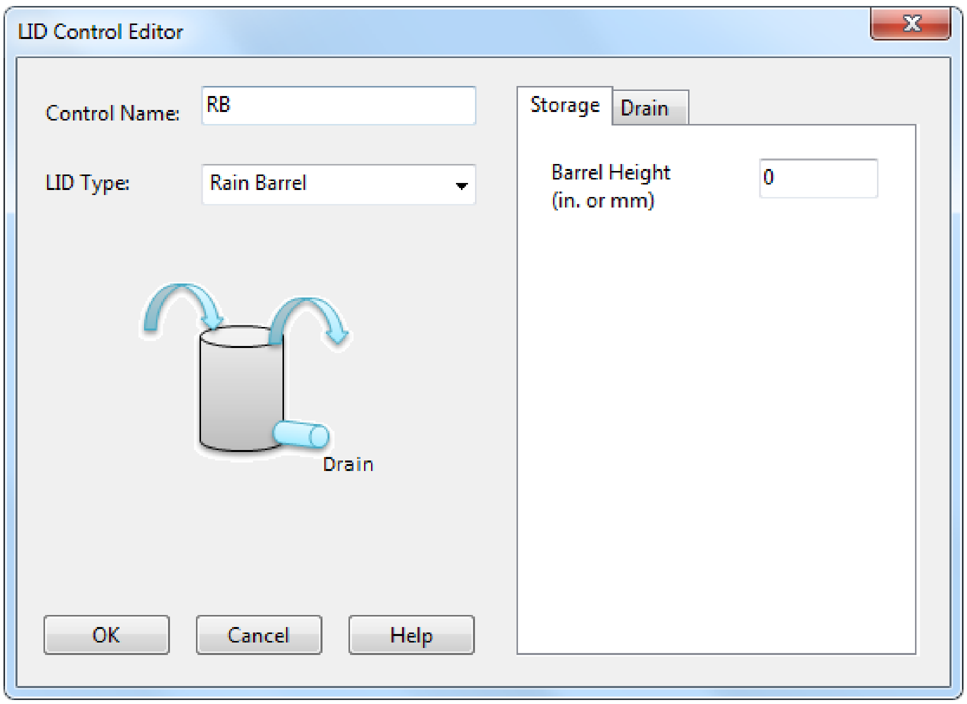


Figure 8. Rain Barrel Control Editor in SWMM5

3.2.3 LID Deployment in SWMM5

Overland flow from LID controls can be modeled in three ways. The first approach is to route impervious subcatchment to pervious subcatchment to receiving node as shown on Figure 9. Pervious area properties are to be matched to LID control design. The pervious area of the subcatchment acts as LID control. This approach is not realistic and does not give accurate results.

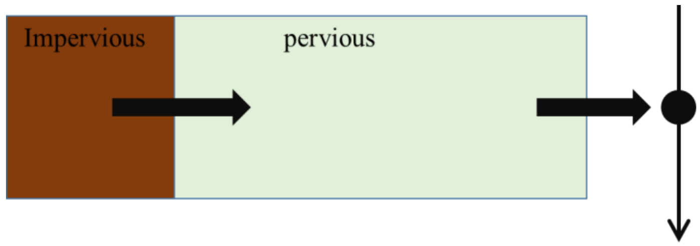


Figure 9. Route Impervious to Pervious Area

The second approach is to create LID subcatchment as a separate subcatchment and to route the original subcatchment to the LID subcatchment to receiving node as shown on Figure 10. The LID design is to be matched to subcatchment properties. LID area is to be extracted from original pervious or impervious area.

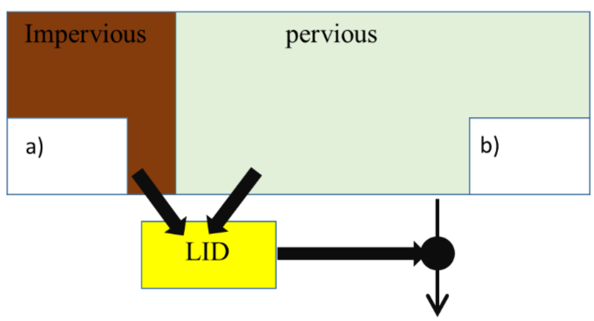


Figure 10. LID as Separate Catchment: a) LID Area Excluded from Impervious Area and b) LID Area Excluded from Pervious Area

The last approach is to create LID as part of original subcatchment and to route runoff through LID prior to receiving node as shown on Figure 11 (USEPA, 2000). LID area is to be added to original pervious or impervious area.

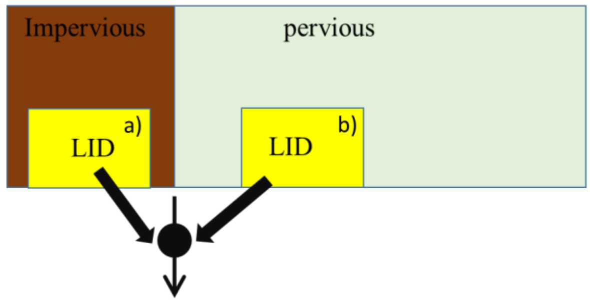


Figure 11. LID Area Included in the Subcatchment: a) LID included in Impervious Area and b) LID included in Pervious Area

If multiple LID units are placed in a subcatchment, then the LID units take the impervious area runoff of a subcatchment. Different capture ratios can be given to different LID units. The options for routing the surface flow and underdrain flow of the LID units are as follows: a) both surface overflow and underdrain flow is routed to the subcatchment's outlet; and b) Underdrain flow can be routed to a separate outlet other than its subcatchment pervious/impervious area.

3.3 Model Setup in SWMM

This section describes about the design storms, study site parameterization and modeling procedure. Details about the precipitation method, and model design are included.

3.3.1 Design Storm

Design storms are synthetic rainfall events based on statistical analysis of rainfall for specific location, representing their occurrence probability for various durations. Therefore, a proper design storm is required to design and evaluate the required performance of hydrologic design. Table 4 shows the rainfall durations and depths for various return periods characterized for Cleveland, OH (NWS, 2014). The rainfall hyetograph chosen for analysis is made for 1 hour duration for different return periods, as shown on Figure 12. The Triangular Hyetograph method is used to calculate the hyetograph (Chow et al., 1988). The total depth of precipitation is given as $h = \frac{2P}{T_d}$, where T_d is the base length and P is the precipitation. The time to peak is calculated by formula $t_a = rT_d$, where r is a storm advancement coefficient for a specific location. This study used the r value of 0.3 given for the State of Ohio (Chow et al., 1988).

Table 4. Precipitation Depth (mm) for Different Return Periods (NWS, 2014)

Duration	**Precipitation Depth (mm)**					
	Return Period (T, years)					
	1	**2**	**5**	**10**	**25**	**50**
5-min	8	10	12	13	15	17
10-min	13	15	18	21	23	26
15-min	16	19	22	25	29	32
30-min	21	25	31	35	41	45
1-hr	25	31	39 [1]	45	53	59
2-hr	29	35	45	52	63	71

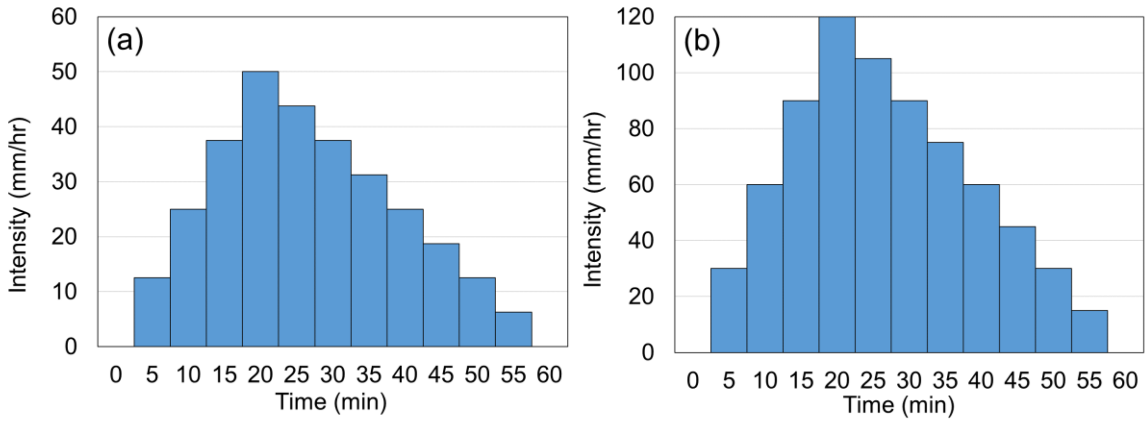


Figure 12. Example of Triangular Rainfall Hyetographs for (a) 25 mm (1-hr 1-year) and (b) 31mm (1-hr 50-year)

3.3.2 Site Parameterization for SWMM

Initially, the site area was modeled using a conventional approach by conceptualizing a subcatchment as residential area and street area as shown on Figure 13(a). Although the model produced acceptable results in non-LID case, it did not consider the bypass flow of the upstream street area to the next downstream street, thus expecting over-predicted peak flow in other simulation. To make the model more realistic, a more hydraulically sophisticated model was built by dividing the residential area into smaller subcatchment units.

This more complex, yet more reasonable approach represented the study site with 126 subcatchments, classified as yard, sidewalk, tree lawn, driveway, apron, house-garage rooftop, and street as shown on Figure 13(b). Runoff is routed from house-garage rooftop to nearby storm sewer whereas yard is routed to tree lawn, tree lawn to sidewalk, side walk to road area. Driveway is routed to apron, apron to road area and road area to the nearby street node. Street nodes (e.g., Node1, Node2, …) in Figure 13(b) represent the nodes which are used to connect street conduit.

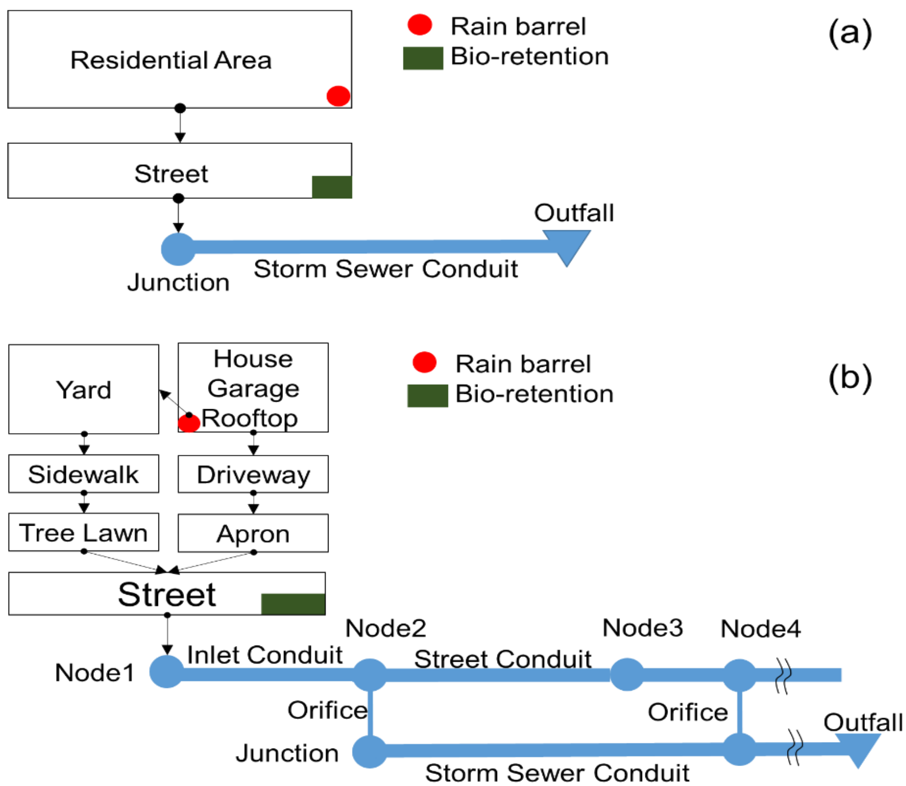


Figure 13.Schematic Diagram of the Subcatchment Conceptualization for SWMM5: (a) Conventional Approach and (b) Revised Approach

There are two types of nodes: 1) street nodes for the street; and 2) junction representing manhole as shown on Figure 13(b). The Figure 13(b) shows the hydraulic connections of street node connected to 'Junction' through orifice.

Street nodes are connected to each other through street conduits, which have an irregular cross-section. A street conduit is a wide-open channel to represent a street that drains direct runoff. For the first two-meter length of street conduit named as 'Inlet

Conduit' in Figure 13(b) represents a shallow conduit to account for a flow in the street and the rest of the length continues as the street conduit. The shallow conduit is used to divert water to street and storm sewer conduit. Junctions are connected through storm sewer conduits.

To more efficiently generate many subcatchments, this study created one complete subcatchment initially, then its configuration and input file (*.inp) were edited to duplicate the subcatchment as required for the whole study site.

3.3.3 Calibration of SWMM5 Parameters

Model calibration plays a crucial role to ensure that the SWMM5 model will properly represent the rainfall-runoff relationship of the study area for a wide range of design storm events. One rainfall-runoff event observed in 2012 by Jarden (2015) was used to calibrate the model parameters. The parameters sensitive to calibration are 'width', '% slope', '% impervious', 'manning's *n* value, and 'depression storage'. As the 'width', '% slope', and '% impervious' are directly measured from the site, this study used the measured values. Therefore, 'Manning's *n* and 'depression storage for impervious area (D-Impervious)' were calibrated to fit the observed flow rate. As the automatic calibration is not available in SWMM5 yet, this study iterated simulations by progressively changing these two parameters until finding the best model performance.

The Nash-Sutcliffe model efficiency coefficient (E) was used to measure the calibration performance (Nash and Sutcliffe, 1970). The E value is computed using Eq. (6) and ranges from -∞ to 1. The closer the E is to 1, the more accurate the model is.

$$E = 1- \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)}{\sum_{t=1}^{T}(Q_0^t - \overline{Q}_o)} \quad (7)$$

where

E is a Nash-Sutcliffe model efficiency coefficient,

Q_m^t is a modeled discharge at time *t*,

Q_o^t is a observed discharge at time *t*, and

$\overline{Q}_o$ is a mean of observed discharge.

The study site is then represented using SWMM objects, such as the subcatchment, nodes, and conduits (Figure 14). Each object visualized in Figure 14 is functional according to its parameters. Each group of subcatchments (yard, sidewalk, tree lawn, driveway, apron, house-garage rooftop, and street) in Figure 14 represents seven houses or 14 houses depending on their locations relative to the street nodes and nearby LID controls. The symbols are used to define conduits and nodes as follows.

- J is a Street node corresponding to north side of the street
- U is a Street node corresponding to south side of the street
- C is a Street conduit connecting "J" nodes
- N is a Street conduit connecting "U" nodes
- JUN is a Node representing manhole
- CO is a Storm sewer conduit connecting "JUN" nodes
- O is a Orifice connecting "J" nodes and "JUN" nodes
- N is a Orifice connecting "U" nodes and "JUN" nodes

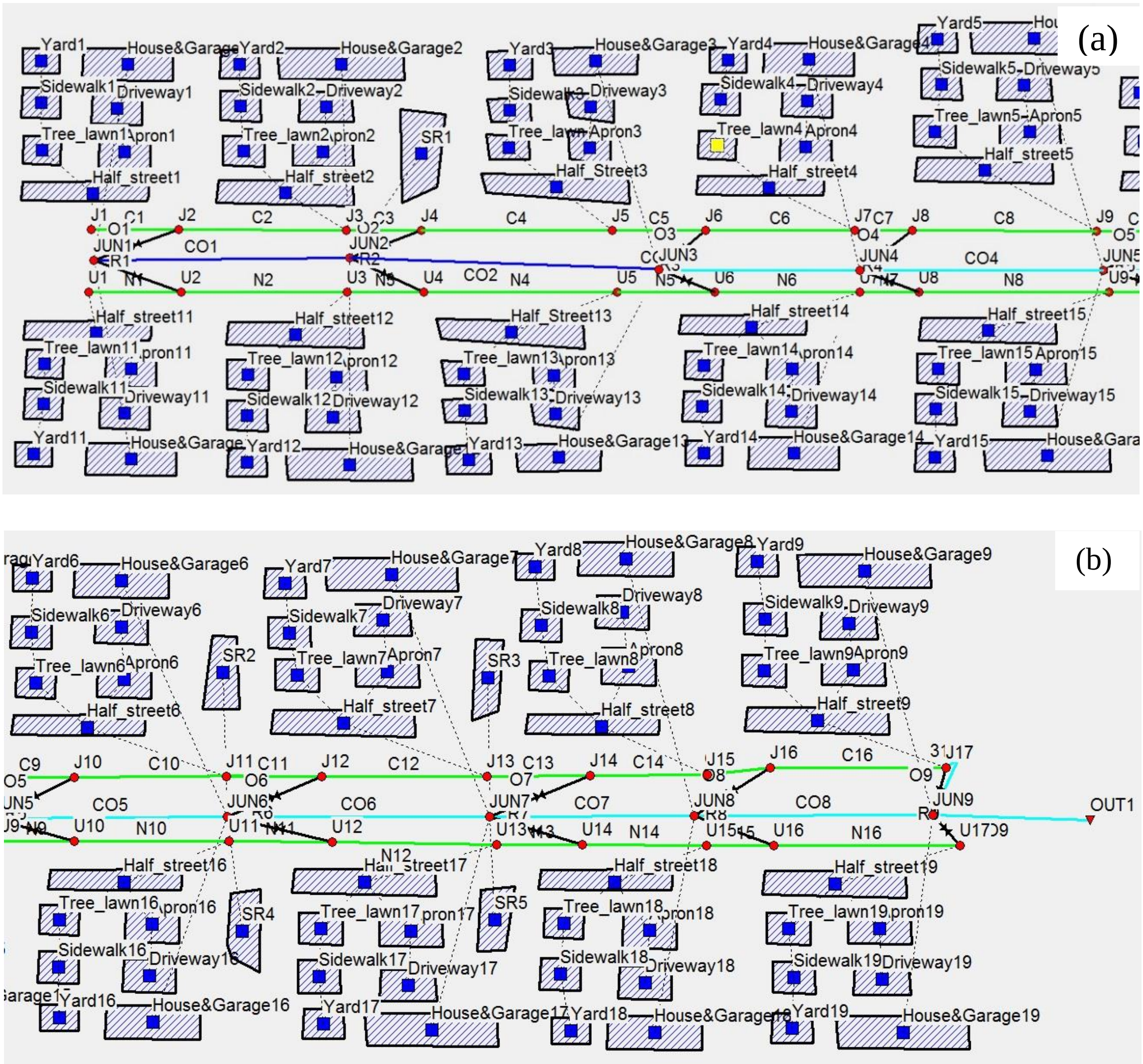


Figure 14. SWMM5 Diagram for Klusner Avenue: (a) West Side and (b) East Side

The subcatchment properties of the study site were parameterized for the SWMM hydrologic module in Table 5. The parameters in Table 5 represents a combined subcatchment for 7 houses. The Green-Ampt infiltration method was selected for surface water runoff model because its parameters are directly estimated from the soil properties and it is a time-based model that simulates the effects of rainfall intensity and duration on infiltration processes. The infiltration capacity of the soil depends on hydraulic conductivity and suction head. Green-Ampt parameters are taken accordingly to the soil type of the study site from the SWMM5 manual (Rossman and Huber, 2016).

Table 5. Subcatchment Properties Parameterized for SWMM5

Properties	**Yard**	**Side-walk**	**Tree Lawn**	**House-Garage Rooftop**	**Drive-way**	**Apron**	**Half-Street**
Area (ha)	0.197	0.0104	0.0425	0.0728	0.0416	0.0107	0.0325
Width (m)	21.34	85.34	68.17	43.45	17.07	21.34	3.81
% Slope	Calculated using Cuyahoga County GIS						
% Impervious	0	100	0	100	100	100	100
n-Impervious[1]	0	0.015	0.015	0.015	0.015	0.015	0.015
n-Pervious	0.2	0.2	0.2	0.2	0.2	0.2	0.2
D-Impervious (mm)[1]	1	1	1	0.01	1	1	1
D-Pervious (mm)	2	2	2	2	2	2	2
Infiltration	Values chosen from SWMM manual using the soil properties						
Suction Head (mm)	200	200	200	200	200	200	200
Conductivity (mm/hr)	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Initial Deficit	0.12	0.12	0.12	0.12	0.12	0.12	0.12

[1] This parameter except Rooftop is calibrated using measured runoff hydrograph (see 3.5)

The properties of junctions and conduits were parameterized for the SWMM hydraulic module and presented in Table 6 and Table 7, respectively. The invert elevation is the elevation of the corresponding junction and the maximum depth is the distance from ground surface to the bottom of the junction. The street node is two meter higher than the junction. So, the invert elevations of street nodes are given by adding two meter to corresponding junction invert elevation. The surcharge depth is the additional water depth above the ground surface used to store water during surcharge conditions. The ponded area is the surface area of the water accumulated during the surcharge while not losing rainfall over the ponded area.

Table 6. Junction Properties used in SWMM5

Junction	Invert Elevation(m)	Maximum Depth (m)
1	332.39	3.23
2	328.29	3.18
3	326.81	3.50
4	324.96	2.13
5	323.78	3.36
6	323.28	3.41
7	322.56	3.16
8	319.50	3.19
9	316.69	3.00

Table 7. Conduit Properties used in SWMM5

Conduit	Shape	Diameter (m)	Length (m)	Manning's *n*[1]	Inlet Offset (m)	Outlet Offset (m)
CO1	Circular	0.305	85.33	0.015	0	0.152
CO2	Circular	0.457	85.33	0.015	0	0.076
CO3	Circular	0.533	170.66	0.015	0	0.152
CO4	Circular	0.610	85.33	0.015	0	0.152
CO5	Circular	0.762	170.66	0.015	0	0
CO6	Circular	0.762	170.66	0.015	0	0
CO7	Circular	0.762	170.66	0.015	0	0
CO8	Circular	0.762	170.66	0.015	0	0
CO9	Circular	0.762	10.59	0.015	0	0

[1] Manning's *n* value is calibrated using measured runoff hydrograph (see 3.5)

The conduits are circular in shape with varying diameter. There is no initial flow in the pipe and entrance and exit losses are negligible. There is no flap gate at the end on the pipe. The dynamic wave routing model is selected for computing flow in conduits and junctions.

As the center of road has higher elevation than the end of the road, street conduit is modeled with irregular cross-section as shown on Figure 15. Street is divided into two equal halves and each halve is modeled with 1V:15H slope. Each half street conduit width is of 3.65 m.

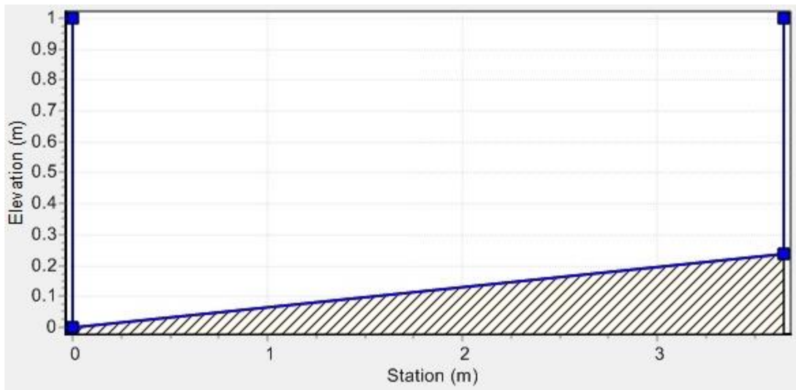


Figure 15. Shape of ‘Half Street’ Conduit Defined in SWMM5

3.4 Simulation Scenarios

The study site was evaluated under the condition before and after installing LID controls. Scenarios are made to analyze the individual effects of different LIDs (Table 8). To study the effect of individual LID practices and for different rainfall depths, scenarios are developed. Scenarios are compared to each other to see the effective LID practice.

Table 8. Simulation Scenarios for Various Combinations of LID Controls

Scenario	Comment	Purpose
1. Base Case	Before LIDs	Reference to other simulation
2. BC	After LIDs: Bio-retention cell only	Effect of bio-retention only
3. RB	After LIDs: Rain barrel only	Effect of rain barrel only
4. BC+RB	After LIDs: Bio-retention and rain barrel	Effect of both LID controls
5. BC+RB-T25	(BC+RB) + Return period 25-year	Evaluation of drainage system with LID controls under 25-year storm
6. BC+RB-T50	(BC+RB) + Return period 50-year	Evaluation of drainage system with LID controls under 50-year storm

3.4.1 Scenario1. Base Case

In this scenario, the street performance before the implementation of LID was modeled. This is considered as the base case model and is simulated for storm events 1H-T1, 1H-T2, 1H-T5, 1H-T10, 1H-T25 and 1H-T50. This case is used as the reference to other simulation scenarios. Note that 1H-T25, for example, indicates a storm with 1-hour (H) duration for 25-year return period (T).

3.4.2 Scenario 2. BC (Bio-retention Cell) only

In this scenario, the effects of bio-retention LID controls were modeled and is simulated for storm events 1H-T1, 1H-T2, 1H-T5, 1H-T10, 1H-T25 and 1H-T50. The properties of bio-retention cells, such as surface area, width, and berm height were estimated from the field trip and Google Earth. Properties of a typical bio-retention cell were parameterized for SWMM LID controls in Table 9.

Table 9. Bio-retention Cell Properties used in SWMM5

Layer	Properties	Values
Surface	Berm Height (mm)	500
	Vegetative Volume Fraction (-)	0.05
	Surface Roughness (-)	0.3
	Surface Slope (%)	1
Soil	Thickness (mm)	500
	Porosity (-)	0.43
	Field Capacity (-)	0.062
	Wilting Point (-)	0.024
	Conductivity (mm/hr)	120
	Conductivity Slope (-)	50
	Suction Head (mm)	49
Storage	Thickness (mm)	500
	Void Ratio (-)	0.75
	Seepage Rate (mm/hr)	4.8
	Clogging Factor (-)	0
Drain	Flow Coefficient (-)	0
	Flow Exponent (-)	0
	Offset Height (mm)	0

Bio-retention is modeled as one of the SWMM LID controls receiving storm from the one lane of a street subcatchment (‘Half street’ in Figure 13(b)). The excess storm water will flow to the nearest street node. A total of 17 bio-retention cells were included in this study. Five bio-retention cells treated an area of 0.013 ha and 12 bio-retention cells treated an area of 0.011 ha. The bio-retention cells were modeled at locations different from its actual on-site location. Step-by-step procedures for modeling a bio-retention cell are as follows:

- In the subcatchment property, choose LID controls and click add.
- Click ‘LID Control Name’ and add ‘BioRetention’ as shown on Figure 16. Enter the parameters values obtained earlier. If there are multiple bio-retention cells in a subcatchment, enter the number of bio-retention cells in ‘Number of Units’ as shown on Figure 16.

- Enter '% of Impervious Treated' by bio-retention, which is the capturing ratio of storm water from the impervious area in a catchment. It is a key parameter to dominate the performance of bio-retention. Depending on the '% of Impervious Treated', the runoff treated varies significantly. This study used 30 % for this value based on the inlet opening size of bio-retention cell. Untreated storm water is routed to a downstream street node
- If bio-retention has an underdrain, underdrain water can be routed to different outlets or the same outlet of subcatchment depending on the design. Click tab below 'Send Drain Flow To' and include the outlet accordingly to the drain design as shown on Figure 16.

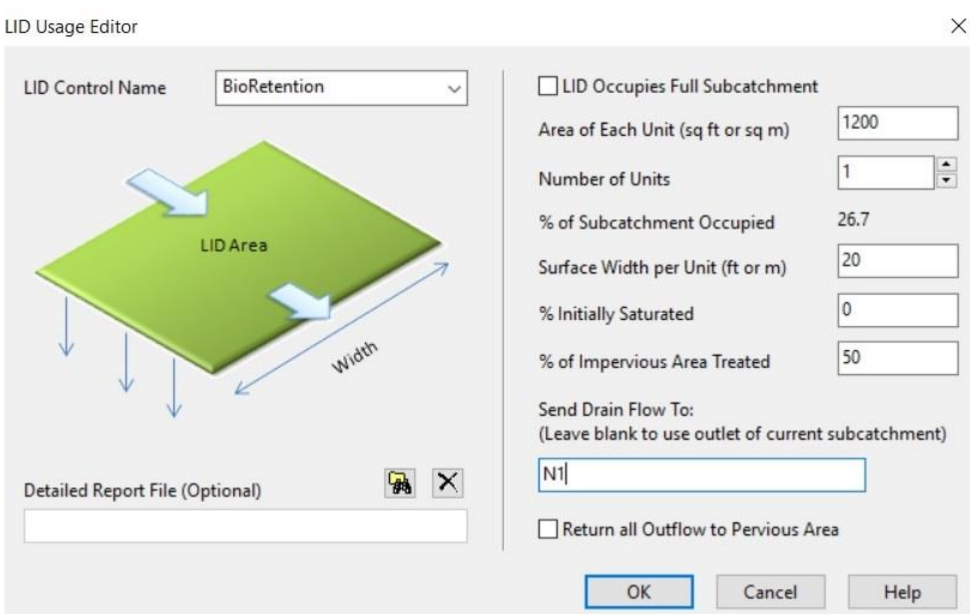


Figure 16. Example of LID Usage Editor in SWMM5

3.4.3 Scenario 3. RB (rain barrel) only

In this scenario, 40 rain barrels were modeled and is simulated for storm events 1H-T1, 1H-T2, 1H-T5, 1H-T10, 1H-T25 and 1H-T50. Standard properties are considered for rain barrel design (Table 10). This rain barrel is added as a LID control to the house and garage rooftops. The excess water (overflow) of rain barrel was diverted to the 'yard subcatchment'. The procedure for modeling of rain barrel is similar to bio-retention. There were 40 rain barrels modeled in this study.

Rain barrel treats 100 % of the house and garage area. The rooftop was assumed as a gable shape with eaves. Each house/garage requires two rain barrels to treat complete rooftop. To efficiently model many rain barrels, one large rain barrel, which is equivalent to four regular rain barrels, was included in a 'House&Garage' catchment if required. The hydraulic properties of an equivalent rain barrel, flow coefficient and the diameter of a drain pipe, were determined by a mass balance equation maintaining the original total outflow flow volume rate and time to empty. It is noted that flow coefficient did not much change the outflow rate after reaching its maximum limit. Flow coefficient values are varied until a constant outflow rate is maintained (this study has a flow coefficient value of 100). The maximum value of flow coefficient where outflow rate remains constant was the limit used in the model.

As each group of subcatchments represents seven houses, seven combined rain barrels (7*4= 28 regular rain barrels) were assigned to one whole catchment and the remaining 12 rain barrels assigned to special three houses modeled as separate subcatchments. Each rain barrel had an area of 0.3825 m^2.

Table 10. Rain Barrel Properties

Layer	Properties	Values
Storage	Barrel Height (mm)	1300
Drain	Flow Coefficient	100
	Flow Exponent	0.5
	Offset Height (mm)	0

3.4.4 Scenario 4. BC+RB

In this scenario, Scenarios 2 and 3 (bio-retention only and rain barrel only, respectively) were modeled in one scenario to see the combined effects of both bio-retention and rain-barrel. This scenario realistically shows the advantages of LID in residential communities and how peak runoff is reduced is determined.

3.4.5 Scenario 5 and 6: BC+RB–T25&BC+RB–T50

The remaining Scenarios 5 and 6 are same as Scenario 4 except they are simulated for the storm event of 1H-T25 and 1H-T50. These two scenarios provide very useful and critical information showing if the current drainage system designed to less than 25-year of storm event and is capable of more intense storm events. These scenarios are particularly important to evaluate the impact of potential climate change.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter describes the results of the hydrologic modeling effort, comparing LID with non-LID for residential development. The data for peak storm flow and total storm volume is analyzed for various storm events.

4.1 Calibration

As described in Chapter 3, the values of Manning's n and depression storage were calibrated to best represent the observed rainfall-runoff relationship of the study area. Table 11 present the calibrated parameters. Parameters were initially set to their default values in SWMM. Under the observed rain event of 12.5 mm in 2012, the calibrated model and observed runoff volume was 618 and 665 m^3, respectively. The error between calibrated and observed runoff volume is -7 % whereas deviation of peaks is 0.3 % as shown on Figure 17(b). The time to peak was accurately simulated by the calibrated model as 30 minutes (Figure 17(b)). The R^2 value was 0.72 and the Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) of 0.69, indicating this calibration performance is acceptable to represent the study site and thus the calibrated model is used to simulate other evaluation scenarios to analyze the effects of LID controls under different design storms.

Table 11. Calibrated Parameters for the Base Case

	Manning's *n*	**D-Impervious**	**Manning's *n* for Conduits**
Before Calibration	0.015	1.0	0.015
After Calibration	0.017	0.5	0.017

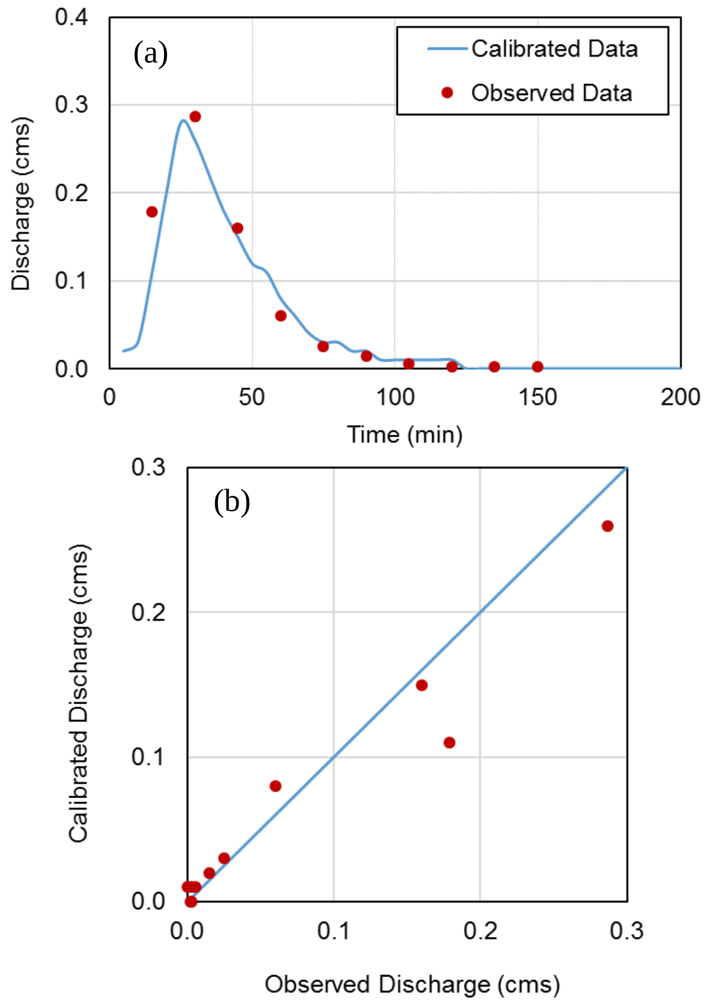


Figure 17. Comparison Between the Observed (Jarden, 2015) and Calibrated Discharge: (a) Hydrographs and (b) Scatter Plot

4.2 Simulation Results

The hydrologic responses of the study site with and without LID controls were evaluated for various catchment scenarios (Tables 13 and 14) using different storm events (1H-T1, 1H-T2, 1H-T5, 1H-T10, 1H-T25 and 1H-T50). Simulation results are compared in terms of total runoff volume, peak flow, and peak arrival time.

4.2.1 Comparison of Conventional and Revised Approaches

The Klusner Avenue was modeled using the conventional and revised methods. The conventional method in Figure 13(a) was built to compare its performance with revised method. The conventional method was simulated for observed event and three rainfall events. The performance varied for observed and other rainfall events. The major difference between the conventional and revised methods is whether to allow the bypass flow or not. For observed rainfall event, the conventional method has higher peak and total volume as all runoff water is directly routed through the main storm sewer system (Table 12). Whereas in the revised method, only a percentage of water is routed through the main storm sewer system and the rest flows to the next street nodes or street conduits before entering to the main storm sewer, thus peak and total volume are attenuated realistically (Table 12).

For higher rainfall events (e.g., 25-year and 50-year), the flow from a street subcatchment is routed to a next street subcatchment hydraulically accounting for bypass flow in the revised method. As rainfall intensity becomes higher, the bypass flow (street channel flow) in the revised method more contributes to the peak flow and total volume at the outfall, compared to conventional method that does not consider bypass flows.

Considering the bypass flow is common in real streets during storm events, the revised method proposed in this study is closer to the real drainage system.

Table 12. Comparison of Conventional and Revised Method for Base Case

Rainfall (mm)	Method	Peak Flow (cms)	Runoff Volume (m^3)	Peak Time (min)	Runoff Ratio
Jarden et al. (2015) (12.45 mm)	Observed	0.287	665	30	0.45
	Conventional	0.332	632	31	0.42
	Revised	0.285	618	30	0.41
1H-T5 (39 mm)	Conventional	1.419	3120	34	0.67
	Revised	1.305	3194	40	0.68
1H-T25 (53 mm)	Conventional	1.700	4743	30	0.75
	Revised	2.109	4815	40	0.76
1H-T50 (60 mm)	Conventional	1.781	5564	30	0.77
	Revised	2.529	5636	39	0.78

4.2.2 Total Runoff Volume

Urbanization generally decreases permeable land cover, which disrupts natural hydrologic cycles in urban areas. The more vegetative covers are the effective solution for preserving hydrologic cycle (Jia, 2012). The negative impacts of expanded impervious area caused by urbanization can be effectively recovered by applying LID controls such as rain barrels and bio-retention cells.

It is reported that the decreased impervious cover by more greenery for 10% residential land cover reduces the runoff volume by 4.9 % (Gill et al., 2007). Luell (2011) observed that bio-retention cells installed in low conductivity soils can reduce runoff volume up to 30% for 25 mm storm events. Although the performance of LID controls is site-specific, it is obvious that LID controls can decrease direct runoff volume while increasing groundwater recharge though surface infiltration. This study simulated the study site with and without LID controls to evaluate their performance to reduce runoff volume for different design storms (Table 13).

Table 13. Total Runoff Volume Simulated for Different Scenarios

Design Storm		**Runoff Volume (m^3)**			
Event	**Depth (mm)**	**Scenario1 (Base Case)**	**Scenario2 (BC)**	**Scenario3 (RB)**	**Scenario4 (BC+RB)**
1H-T1	25	1638	1466 (-10.5%)[1]	1615 (-1.4%)	1439 (-12.1%)
1H-T2	31	2292	2040 (-11.0%)	2270 (-1.0%)	2008 (-12.4%)
1H-T5	39	3194	2830 (-11.4%)	3172 (-0.7%)	2791 (-12.7%)
1H-T10	45	3884	3442 (-11.4%)	3862 (-0.6%)	3401 (-12.5%)
1H-T25	53	4815	4314 (-10.4%)	4794 (-0.4%)	4297 (-10.7%)
1H-T50	60	5636	5128 (-9.0%)	5613 (-0.4%)	5113 (-9.3%)

[1] Values inside parenthesis indicate the percent changes from Base Case.

With two LID controls (BC and RB), the total volume reductions are simulated from 9 to 12 % compared to Base Case (last column in Table 13). LIDs are designed to capture the lesser storm events (less than a 25-year of storm). Hence, during intense storm events (over 25-year return period), LIDs quickly reach their capacities and overflows to nearby junctions. As pointed out earlier, the reduction in total volume decreases as storm event intensity varies due to the increased bypass flow in street nodes and conduits toward the main junctions.

Overall, bio-retention only (BC) shows more reductions in runoff volume than rain-barrel only (RB). It is difficult to compare their performance directly because those two LIDs capture the different ranges of impervious areas. It is noted that rain barrels in the study site captures only nine houses out of 200 houses, which is equivalent to an impervious area of 0.12 ha, while bio-retention cells in the study site treat a total 0.51 ha of impervious area consisting of streets surface combined with the runon routed from driveways/apron, assuming 33% of surface runoff are captured by bio-retention cells.

In case of 1 year return period for example, the percent volume reduction ratio (BC to RB) is about 7.5 (=10.5%/1.4%), while the ratio of impervious area captured by BC and RB is about 4.3 (=0.51 ha/0.12 ha). The runoff volume reduction ratio between BC and RB increases up to about 22 for 25-year and 50-year storms.

The relative performance with regard to the treatment area of each LID can be interpreted as 1.7 (=7.5/4.3), where unity means equal performance between two LIDs. The relative performance ranges from 1.7 (1-year storm) to about 5.1 (=22/4.3) (25-year and 50-year storm), implying bio-retention cells are more effective than rain barrels, especially in intensive storm. The results simulated in this study is consistent with the previous observation for the same study site conducted by Jarden et al (2015). This trend indicates that the performance of a LID control depends on its capturing area as well as its own storm water reduction capacity.

Therefore, bio-retention cells installed in the study site outperformed in volume reduction per unit impervious area over rain barrels. However, it is noted that bio-retention cells require more complicated engineering design, favorable soil conditions, and expensive construction cost. Especially, it needs voluntarily participation to allow installation within private property. On the other hand, rain barrels are easy to install without large property occupancy.

4.2.3 Peak Flow and Peak Time

In this section, peak flow and its arrival time are compared for all LID control scenarios with Base Case as shown on Tables 14 and 15, respectively. Figure 18 compares the hydrographs for all simulation scenarios indicating BC and RB are capable of reducing peak flow and runoff volume.

The reduction in peak flow under both LID controls ranges from 11.4 to 14.7% for various design storm events, compared to Base Case. It is not reasonable to compare with the performance of bio-retention cells directly as bio-retention cells in the study site treat about 5 times of impervious area than rain barrels treat.

Similarly to the previous section (runoff volume), the relative performance of bio-retention cells over rain barrels ranges from 1.2 (= 5.3/4.3, where 5.3 = 9.5/1.8 for 1-year storm) to 9.7 (= 41.7/4.3, where 41.7 = 12.5/0.3 for 50-year storm). This analysis implies that bio-retention cells are more capable of treating large storm event than rain barrels.

Table 14. Peak Flow Simulated for Different Scenarios

Design Storm		**Peak Flow (cms)**			
Event	**Depth (mm)**	**Scenario1 (Base Case)**	**Scenario2 (BC)**	**Scenario3 (RB)**	**Scenario4 (BC+RB)**
1H-T1	25	0.622	0.563 (-9.5%)	0.611 (-1.8%)	0.551 (-11.4%)
1H-T2	31	0.890	0.793 (-10.9%)	0.878 (-1.3%)	0.779 (-12.5%)
1H-T5	39	1.305	1.141 (-12.6%)	1.292 (-1.0%)	1.124 (-13.9%)
1H-T10	45	1.646	1.428 (-13.2%)	1.631 (-0.9%)	1.409 (-14.4%)
1H-T25	53	2.109	1.822 (-13.6%)	2.099 (-0.5%)	1.800 (-14.7%)
1H-T50	60	2.529	2.215 (-12.5%)	2.522 (-0.3%)	2.183 (-13.7%)

Studies performed around the United States on rain barrels have shown a spectrum of results ranging from a 44% runoff reduction in the southwestern states to 3% in southeastern states (Litofsky, 2014). As rain barrels with a typical capacity less than 200 L disconnect downspouts from roofs and drains roof water into back yards, the performance of rain barrels is dependent of soil properties. The primary reason of inferior performance of rain barrels is their smaller capturing area than bio-retention cells, similar to the observations in runoff volume reduction. However, rain barrels provide garden irrigation by diverting water to garden and backyards.

Peak time simulated from all scenarios is similar to each other because the study site is a small residential catchment yielding a short travel time generally (i.e., time of concentration) (Figure 18(a)). Notable observation is rain barrels are effective to delay peak time in low rainfall intensities (2-year and 5-year storms) except the 1-year storm event. It is assumed that there were numerical fluctuations to compute the propagation of flood wave in shallow water in SWMM. It remains as a research question in the future. It is generally observed that LID controls is not significantly effective to delay the peak time in small urban watershed, compared to non-LID condition (Base Case).

Table 15. Peak Time Simulated for Different Scenarios

Design Storm		**Peak Time (min)**			
Event	**Depth (mm)**	**Scenario1 (Base Case)**	**Scenario2 (BC)**	**Scenario3 (RB)**	**Scenario4 (BC+RB)**
1H-T1	25	40	40	40	40
1H-T2	31	40	40	43	40
1H-T5	39	40	40	42	40
1H-T10	45	40	40	40	40
1H-T25	53	40	40	40	40
1H-T50	60	39	41	40	41

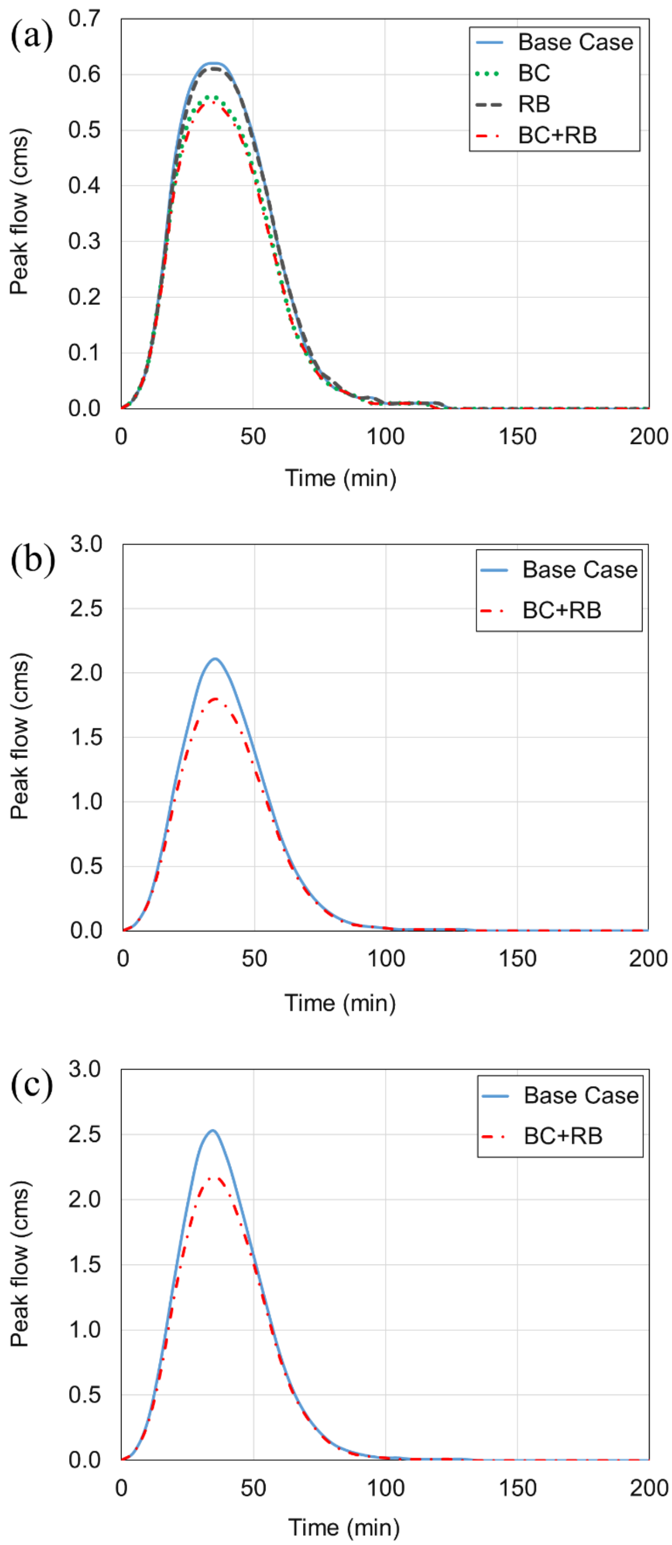


Figure 18. Peak Flow Comparison for Simulation Scenarios: (a) Comparison of Scenarios 1 to 4 for Storm Event 1H-T1, (b) Scenario 5, and (c) Scenario 6 (See Table 8 for Scenarios)

4.2.4 Water Surface Profile

Because the recommended return period of design storm for residential area is 5-year (Cuyahoga County Sanitary Engineering Division, 1998), it is important to evaluate if the current drainage system can treat higher rainfall intensity under changing climate conditions. Water surface profiles were plotted using SWMM5 for the main storm sewer network to evaluate the surcharge effects under higher design storms (e.g., 50-year return period). Figure 19 shows the highest water surface profiles simulated under both non-LID condition (Base Case, Figure 19(a)) and two LID controls (Figure 19(b)) under a design storm of 50-year return period. It is observed that there is no surcharge at main junctions over all time steps in both scenarios. The case with LID controls in Figure 19(b) shows slightly lower water elevations in Junctions 4 to 6 with inflow values ranging from 0.406 to 0.635 compared to the non-LID case inflow values ranging from 0.424 to 0.692 respectively (Figure 19(a)). Although the drainage system under current land management is safe for a 50-year storm event, the study site can be more reliable to intense storms by expanding LID controls continuously.

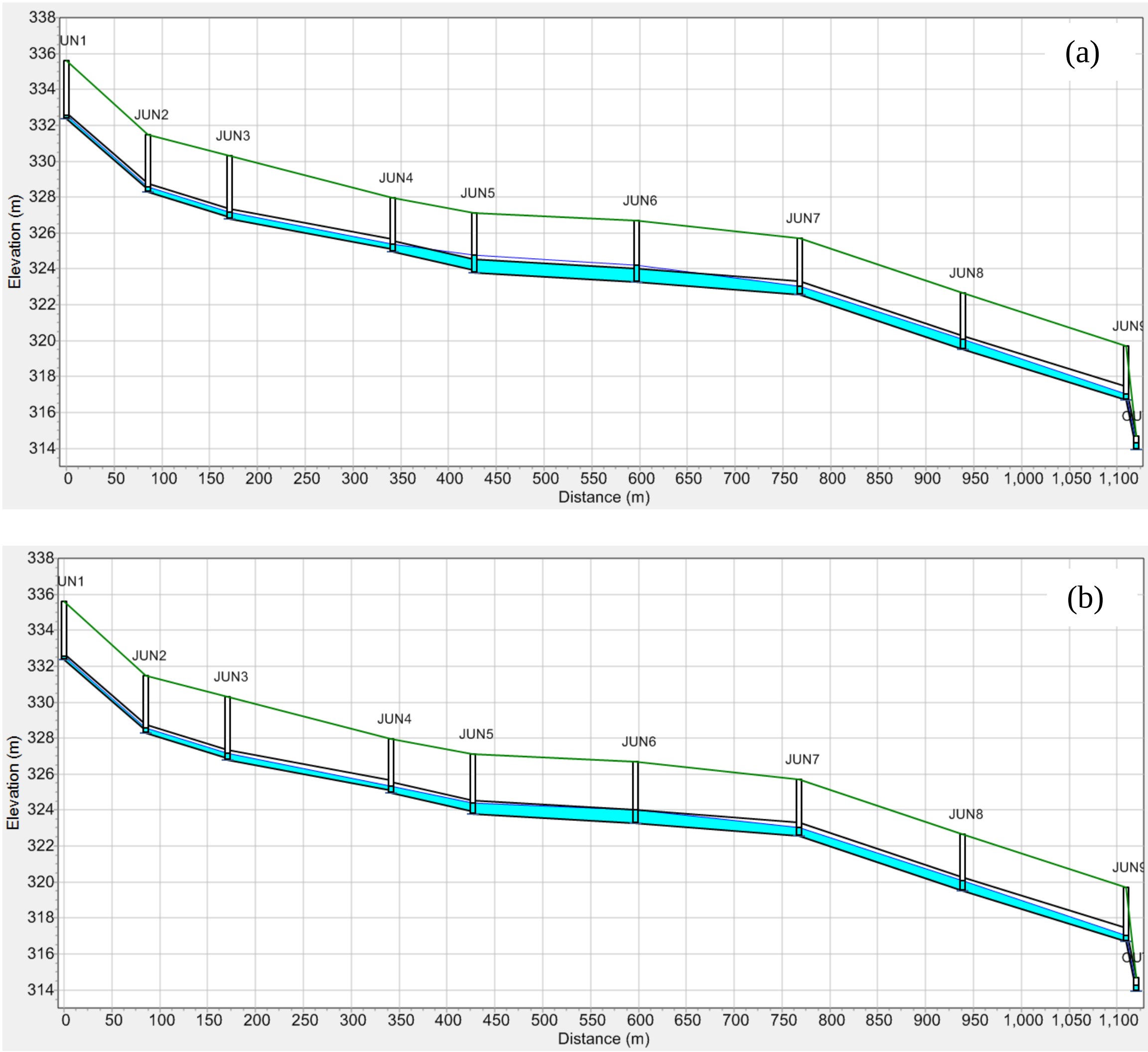


Figure 19. Water Surface Profile Captured at the Peak Flow for Design Storms 1H-T50: (a) without LID control and (b) with LID control.

CHAPTER V

SUMMARY AND CONCLUSION

LID practices have been shown to produce considerable reduction in runoff and peak flows in urban storm water systems. In this study, the effect of LID implementation on runoff and peak flow mitigation in Klusner Avenue, Parma, Ohio was modeled in SWMM5 and was simulated for different rainfall periods. This study provided a detailed modeling procedure for residential streets.

Residential houses have been broken into smaller subcatchments and bypass flow from one street to next street is accounted for to enhance the model and to improve routing methodologies. Street drawings were collected from NEORSD for measuring elevations of junctions and to measure conduit diameters. Cuyahoga County GIS were analyzed for measurements of area, slope, width, and impervious area of the study area. Previously observed rainfall- runoff event was used in parameter calibration to apply SWMM5 to other simulations including LID controls. LID controls were modeled using SWMM5 LID modules and hydraulic street runoff routing to see the effects of bio-retention and rain barrels on runoff reduction in an urban area.

Major findings are summarized as follows.

1) Comparing conventional approaches that over-simplify the hydrologic and hydraulic components of a subcatchment, the revised approach proposed in this study considered more realistic runoff routing through street surfaces by accounting bypass flow from one street to next street which is very common in street drainage systems.
2) The runoff volume reduction simulated using a combination of bio-retention and rain barrel (BC+RB) ranges from 9.3% to 12.7% for different storm events, compared to the base case. The results showed that the LID controls have considerable positive effects on storm water management. Whereas the relative performance of BC over RB with respect to treatment area of respective LID ranges from 1.7 to 5.1 (1-year and 50-year storm, respectively) showing bio-retention outperformed than rain barrels. Even though results showed that the bio-retention performance outweighed more than rain barrels, it is to be noted that rain barrels are easy to install and maintain with smaller areal occupancy.
3) The peak flow reduction rates under a combination of BC+RB are from 11.4% to 14.7%, compared to the base case. The relative performance of BC to RB with respect to treatment area of respective LID ranges from 1.2 to 9.7 (1-year and 50-year storm, respectively). In the model, rain barrels treat 1% of the total area whereas bio-retention treats 4.3%. Hence, further reduction in runoff can be observed by adding more green infrastructure practices.

4) The water surface profile for a more intense storm (50-year return period) simulated under current LID controls shows the release of surcharges that occurred in non-LID conditions. Considering that the current drainage system was designed to withstand 5-year storm, it is expected that the study area can effectively control the flood beyond this design capacity.
5) This study provided a detailed modeling procedure that can be applied to other residential streets to evaluate the effects of LID on their storm water system. Especially, by conceptualizing the storm water runoff in street surface as open-channel flow, the LID modeling framework suggested in this study is general to simulate other similar types of LID controls.

Though there are similar percent reductions (about 11%) in runoff volume for the return periods from 1-year to 10-year, the percent runoff volume reduction decreased as a rainfall intensity increases beyond 10-year return period indicating the LID controls in the study area is out of capacity under higher storm events. Therefore, the runoff volume reduction rate varies depending to the storm event as well as the number of locations and sizes of bio-retentions and rain barrels. These findings demonstrate that proper LID sizing and design are essential to maximize their benefits under given storm water management policy. Performance of rain barrels can be improved by increasing the roof treatment area and the capacity of a rain-barrel. Performance of bio-retention can be improved by increasing the surface area being treated by bio-retention or by changing the bio-retention design like soil composition, storage height, conductivity, and berm height. As LID controls mainly rely on the underlined soil characteristics, there is a certain yielding point beyond which the performance improves rarely.

The main reason for households to implement LIDs is improved aesthetics which results in increased property values. Also, it reduces storm water bills to households. Furthermore, it reduces energy consumption needs, costs to build storm drain infrastructure, water treatment costs, and reduces property damage from flooding which makes space healthier. This study helps the communities in planning a valuable step for new sustainable urban development. This study is beneficial to water resources engineers who want to evaluate the effect of different LIDs at a particular site prior to its implementation.

Although this study properly considered the effect of LID locations and sizes in the modeling processes by introducing relative performance of each LID, the analysis of cost-to-benefit representing percent runoff volume reduction per unit cost could not be conducted due to lack of published cost information. To determine a more cost-effective LID controls, a preliminary cost-to-benefit analysis is suggested to be performed in addition to site characterization.

REFERENCES

Abi Aad, M. P., Suidan, M. T., & Shuster, W. D. (2010). Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using EPA SWMM-5. *Journal of Hydrologic Engineering, 15*(6), 434-443. doi:10.1061/(asce)he.1943-5584.0000136.

Arnell, N. W. (1999). The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environmental Change, 9*(1), 5-23. doi:10.1016/s0959-3780(98)00015-6.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious Surface Coverage: The Emergence of a Key Environmental Indicator. *Journal of the American Planning Association, 62*(2), 243-258. doi:10.1080/01944369608975688.

MPCA (Minnesota Pollution Control Agency). (2015). *Minnesota Stormwater Manual*. Retrieved on December 31, 2016, from https://stormwater.pca.state.mn.us/index.php?title=Bio-retention_combined&oldid=23048.

Booth, D. B. (1991). Urbanization and the Natural Drainage System—Impacts, Solutions, and Prognoses. *The Institute for Environmental Studies, 7(1).*

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). *Applied hydrology*. New York: McGraw-Hill.

Clark, S. E., Steele, K. A., Spicher, J., Siu, C. Y., Lalor, M. M., Pitt, R., & Kirby, J. T. (2008). Roofing Materials' Contributions to Storm-Water Runoff Pollution. *Journal of Irrigation and Drainage Engineering, 134*(5), 638-645. doi:10.1061/(asce)0733-9437(2008)134:5(638).

Coffman, L. (2000). Low-impact development design strategies, an integrated design approach. *Prince George's County, Maryland: Department of Environmental Resources, Programs and Planning Division.*

Coffman, L. S., & France, R. L. (2002). Low-impact development: an alternative stormwater management technology. *Handbook of water sensitive planning and design*, 97-123.

Combined sewer. (2016, November 5). *In Wikipedia, The Free Encyclopedia.* Retrieved 21:43, November 5, 2016, from https://en.wikipedia.org/w/index.php?title=Combined_sewer&oldid=748021885.

County, P. G. S. (1999). Low-impact development design strategies: An integrated design approach. *Department of Environmental Resources, Programs and Planning Division, Prince George's County, Maryland.*

Cronshey, R. (1986). *Urban hydrology for small watersheds*. Washington, D.C.: U.S. Department of Agriculture, Soil Conservation Service, Engineering Division.

Cuyahoga County GIS. (2016). *MyPlace Full Map.* Retrieved April 9, 2016 from https://maps.cuyahogacounty.us/.

Cuyahoga County Sanitary Engineering Division (1998). *Uniform Standards for Sewerage Improvements*. Retrieved Jan 10, 2016, from http://publicworks.cuyahogacounty.us/pdf_sanitaryeng/en-US/UniformStandards/stand.pdf.

Davis, A. P. (2008). Field Performance of Bio-retention: Hydrology Impacts. *Journal of Hydrologic Engineering*, *13*(2), 90-95. doi:10.1061/(asce)1084-0699(2008)13:2(90).

Davis, A. P., Hunt, W. F., Traver, R. G., & Clar, M. (2009). Bio-retention Technology: Overview of Current Practice and Future Needs. *Journal of Environmental Engineering, 135*(3), 109-117. doi:10.1061/(asce)0733-9372(2009)135:3(109).

Dietz, M. E. (2007). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Water, Air, and Soil Pollution*, *186*(1-4), 351-363. doi:10.1007/s11270-007-9484-z.

Dietz, M. E., & Clausen, J. C. (2008). Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management*, *87*(4), 560-566. doi:10.1016/j.jenvman.2007.03.026.

Frazer, L. (2005). Paving Paradise: The Peril of Impervious Surfaces. *Environmental Health Perspectives, 113*(7), A456–A462.

Huber, W. C. (2003). Hydrologic Modeling Processes of the EPA Storm Water Management Model (SWMM). *World Water & Environmental Resources Congress 2003*. doi:10.1061/40685(2003)164.

Jang, S., Cho, M., Yoon, J., Yoon, Y., Kim, S., Kim, G., Aksoy, H. (2007). Using SWMM as a tool for hydrologic impact assessment. *Desalination*, *212*(1-3), 344-356. doi: 10.1016/j.desal.2007.05.005.

Jarden, K. (2015). *Assessing Hydrologic Impacts of Street-Scale Green Infrastructure Investments for suburban Parma, Ohio*. (Electronic Thesis or Dissertation). Retrieved from https://etd.ohiolink.edu/.

Jarden, K. M., Jefferson, A. J., & Grieser, J. M. (2015). Assessing the effects of catchment-scale urban green infrastructure retrofits on hydrograph characteristics. *Hydrological Processes,30*(10), 1536-1550. doi:10.1002/hyp.10736.

Jefferson, A. (2013, March 12). Combined sewer overflows: Solving a 19th century problem in the 21st century. Retrieved January 01, 2017, from http://all-geo.org/highlyallochthonous/2013/03/combined-sewer-overflows-solving-a-19th-century-problem-in-the-21st-century/.

Jennifer G., James R., Claire W., Katherine G. H., Derek S. (2016). West Creek Ecosystem Restoration Project: Neighborhood Storm Water Stewardship Initiative. *Cleveland Metro parks, URS and West Creek Conservancy*. Retrieved December 31, 2016, from http://www.prrsum.org/sites/prrsum.org/files/Grieser_flood_AOP_crit_infra_talk_umsrs.pdf.

Jennings, A. A., Adeel, A. A., Hopkins, A., Litofsky, A. L., & Wellstead, S. W. (2013). Rain Barrel–Urban Garden Stormwater Management Performance. *Journal of Environmental Engineering,139*(5), 757-765. doi:10.1061/(asce)ee.1943-7870.0000663.

Litofsky, A. L., Jennings, A. A. (2014). Evaluating Rain Barrel Storm Water Management Effectiveness across Climatography Zones of the United States.

Journal of Environmental Engineering,140(4), 04014009. doi:10.1061/(asce)ee.1943-7870.0000815.

Jia, H., Lu, Y., Yu, S. L., & Chen, Y. (2012). Planning of LID–BMPs for urban runoff control: The case of Beijing Olympic Village. *Separation and Purification Technology, 84*, 112-119. doi: 10.1016/j.seppur.2011.04.026.

Lyandres O, Welch L.C. (2012, June 21). *Reducing Combined Sewer Overflows in the Great Lakes: Why Investing in Infrastructure is Critical to Improving Water Quality.* Retrieved January 01, 2017, from http://bnriverkeeper.org/2012/06/reducing-combined-sewer-overflows-in-the-great-lakes-why-investing-in-infrastructure-is-critical-to-improving-water-quality/.

Luell, S. (2011). *Evaluating the Impact of Bioretention Cell Size and Swale Design in Treating Highway Bridge Deck Runoff.* (Electronic Thesis or Dissertation). Retrieved from http://www.lib.ncsu.edu/resolver/1840.16/6921.

Maloney, K. (2015, September 15*). Sewer District Permitted to Manage Stormwater and Charge Fee*. Retrieved January 01, 2017, from http://www.courtnewsohio.gov/cases/2015/SCO/0915/131770.asp#.V7oGMPkrKJA.

McCutcheon, M. (2013, May 9). *SWMM5 LID control for Green Infrastructure Modeling* [Presentation slides]. Retrieved January 01, 2017, from http://www.ohiowea.org/docs/1115_SWMM5_LID_Control_Green_Infrastructure_M odeling.pdf.

Mccutcheon, M., & Wride, D. (2013). Shades of Green: Using SWMM LID Controls to Simulate Green Infrastructure. *Journal of Water Management Modeling.* doi:10.14796/jwmm.r246-15.

Mccutcheon, M., Wride, D., & Reinicke, J. (2012). An Evaluation of Modeling Green Infrastructure Using LID Controls. *Journal of Water Management Modeling.* doi:10.14796/jwmm.r245-12.

Meyers, R. (2015). *Ohio Supreme Court Says Sewer District Can Charge Storm Water Fees*. Retrieved December 31, 2016, from http://meyersroman.com/ohio-supreme-court-says-sewer-district-can-charge-stormwater-fees/.

NAHB (National Association of Home Builders). (2003). *The practice of low impact development*. Prepared for U.S. Dept. of Housing and Urban Development, Office of Policy Development and Research. Upper Marlboro, Maryland.

Nash, J. E. & J. V. Sutcliffe (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, *10* (3), 282–290.

NEORSD (Northeast Regional Sewer District). (2017) *West Creek Watershed*. Retrieved January 01, 2017, from https://www.neorsd.org/west_creek_watershed.php.

NEORSD. (2016). *Storm water Fee Credit Policy Manual*. Retrieved July 16, 2016, from http://www.neorsd.org/I_Library.php?a=download_file&LIBRARY_RECORD_ID=4699.

NWS (National Weather Service). (2014). *Atlas 14 Point Precipitation Frequency Estimate: OH (Volume 2 Version 3)* [Data Set]. Retrieved from http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=md.

Pyke, C., Warren, M. P., Johnson, T., Lagro, J., Scharfenberg, J., Groth, P., . . . Main, E. (2011). Assessment of low impact development for managing storm water with changing precipitation due to climate change. *Landscape and Urban Planning, 103*(2), 166-173. doi: 10.1016/j.landurbplan.2011.07.006.

Rosa, D. J. (2013). *Post-audit Verification of the Model SWMM for Low Impact Development* (Master's thesis). Retrieved from http://digitalcommons.uconn.edu/cgi/viewcontent.cgi?article=1518&context=gs_theses.

Rossman, L. A. (2010). Storm water management model user's manual, version 5.0 (p. 276). *Cincinnati, OH: National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.*

Rossman, L., & Huber, W. (2016). Storm water management model reference manual: Volume I–Hydrology (revised). *US Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Cincinnati, OH*, 45268.

Rossman, L., & Huber, W. (2016). Storm water management model reference manual: Volume III – Water Quality. *US Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Cincinnati, OH*, 45268.

Roy-Poirier, A., Champagne, P., & Filion, Y. (2010). Review of Bio-retention System Research and Design: Past, Present, and Future. *Journal of Environmental Engineering, 136*(9), 878-889. doi:10.1061/(asce)ee.1943-7870.0000227.

Shafique, M., & Kim, R. (2015). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. *Ecological Chemistry and Engineering S, 22*(4). doi:10.1515/eces-2015-0032.

Tsihrintzis, V. A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: a review. *Water Resources Management, 11*(2), 136-164.

USEPA (U.S. Environmental Protection Agency). (2000). Low Impact Development (LID): A Literature Review. *United States Environmental Protection Agency, Washington, D.C*. EPA-841-B-00- 005.

USDA (United States Department of Agriculture). (2016). *Web Soil Survey*. Retrieved December 31, 2016, from http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

Wahl, M., Mckellar, H., & Williams, T. (1997). Patterns of nutrient loading in forested and urbanized coastal streams. *Journal of Experimental Marine Biology and Ecology, 213*(1), 111-131. doi:10.1016/s0022-0981(97)00012-9.

Wang, L., Lyons, J., Kanehl, P., & Bannerman, R. (2001). Impacts of Urbanization on Stream Habitat and Fish Across Multiple Spatial Scales. *Environmental Management, 28*(2), 255-266. doi:10.1007/s0026702409.

Winston, RJ., Dorsey, JD., & Hunt, WF. (2016). Quantifying volume reduction and peak flow mitigation for three bio-retention cells in clay soils in northeast Ohio. *Science of The Total Environment,* 553, 83-95. doi:10.1016/j.scitotenv.2016.02.081.

World population. (2017, April 28). *In Wikipedia*, *The Free Encyclopedia*. Retrieved 15:23, April 28, 2017, from https://en.wikipedia.org/w/index.php?title=World_population&oldid=777624930

APPENDICES

A. CALIBRATION DATA

Time (Sep 3, 2012)	Rainfall (mm)	Discharge (cms)
19:30	1.52	0.00
19:45	8.13	0.03
20:00	10.67	0.28
20:15	12.19	0.18
20:30	12.19	0.11
20:45	12.45	0.04
21:00	12.45	0.02
21:15	12.45	0.01
21:30	12.45	0.01

B. SWMM INPUT FILE

(1) Conventional Subcatchment Conceptualization

NOTE: The input file runs for 1-year storm event. To model for all events in a single input file, change the '[RAINGAGES]' for each design storm, and substitute the appropriate 'TIMESERIES'.

[TITLE]	
Project	Title/Notes
[OPTIONS]	
Option	Value
FLOW_UNITS	CMS
INFILTRATION	GREEN_AMPT
FLOW_ROUTING	DYNWAVE
LINK_OFFSETS	DEPTH
MIN_SLOPE	0
ALLOW_PONDING	YES
SKIP_STEADY_STATE	NO
START_DATE	4/30/2016
START_TIME	0:00:00
REPORT_START_DATE	4/30/2016
REPORT_START_TIME	0:00:00
END_DATE	5/2/2016
END_TIME	6:00:00
SWEEP_START	1-Jan
SWEEP_END	31-Dec
DRY_DAYS	0
REPORT_STEP	0:01:00
WET_STEP	0:05:00
DRY_STEP	6:00:00
ROUTING_STEP	0:00:01
INERTIAL_DAMPING	PARTIAL
NORMAL_FLOW_LIMITED	BOTH
FORCE_MAIN_EQUATION	H-W
VARIABLE_STEP	0.75
LENGTHENING_STEP	0
MIN_SURFAREA	1.14
MAX_TRIALS	8
HEAD_TOLERANCE	0.0015
SYS_FLOW_TOL	5
LAT_FLOW_TOL	5
MINIMUM_STEP	0.5
THREADS	1

***INSERT RAINGAGE DATA BELOW*:**

[RAINGAGES]

Name	Format	Interval	SCF	Source
RG1	INTENSITY	0:05	1	TIMESERIES triangular_1hr_1yr

INSERT SUBCATCHMENT DATA BELOW:

[SUBCATCHMENTS]

Name	Rain Gage	Outlet	Area	%Imp	Width	%Slope
K11	RG1	J1	0.382	35	90	3.86
K12	RG1	J2	0.382	35	90	4
K13	RG1	J3	0.382	35	90	1.74
K14	RG1	J4	0.382	35	90	1.11
K15	RG1	J5	0.382	35	90	1.11
K16	RG1	J6	0.382	35	90	1.04
K17	RG1	J7	0.382	35	90	0.44
K18	RG1	J8	0.382	35	90	0.44
K19	RG1	J9	0.382	35	90	1.92
K20	RG1	J10	0.382	35	90	1.92
K21	RG1	J11	0.382	35	90	2
K22	RG1	J12	0.382	35	90	2
KR11	RG1	J1	0.0325	100	3.65	3.86
KR12	RG1	J2	0.0325	100	3.65	4.84
KR13	RG1	J3	0.0325	100	3.65	1.74
KR14	RG1	J4	0.0325	100	3.65	1.11
KR15	RG1	J5	0.0325	100	3.65	1.11
KR16	RG1	J6	0.0325	100	3.65	1.04
KR17	RG1	J7	0.0325	100	3.65	0.44
KR18	RG1	J8	0.0325	100	3.65	0.44
KR19	RG1	J9	0.0325	100	3.65	1.92
KR20	RG1	J10	0.0325	100	3.65	1.92
KR21	RG1	J11	0.0325	100	3.65	2.02
KR22	RG1	J12	0.0325	100	3.65	2.02
KR00	RG1	J13	0.0325	100	3.65	1.94
KR01	RG1	J14	0.0325	100	3.65	1.94
R1	RG1	J14	0.065	100	8	2
R2	RG1	J4	0.06	100	8	2
R4	RG1	J4	0.065	100	8	2
R3	RG1	J8	0.065	100	8	2
R5	RG1	J8	0.065	100	8	2
S11	RG1	J1	0.382	35	90	3.86
S12	RG1	J2	0.382	35	90	4
S13	RG1	J3	0.382	35	90	1.74
S14	RG1	J4	0.382	35	90	1.11
S15	RG1	J5	0.382	35	90	1.11
S16	RG1	J6	0.382	35	90	1.04
S17	RG1	J7	0.382	35	90	0.44
S18	RG1	J8	0.382	35	90	0.44
S19	RG1	J9	0.382	35	90	1.92
S20	RG1	J10	0.382	35	90	1.92
S21	RG1	J11	0.382	35	90	2
S22	RG1	J12	0.382	35	90	2
S27	RG1	J14	0.382	35	90	2
S28	RG1	J14	0.382	35	90	2
S29	RG1	J13	0.382	35	90	2
S30	RG1	J13	0.382	35	90	2
SR11	RG1	J1	0.0325	100	3.65	3.86
SR12	RG1	J2	0.0325	100	3.65	4.84
SR13	RG1	J3	0.0325	100	3.65	1.74
SR14	RG1	J4	0.0325	100	3.65	1.11
SR15	RG1	J5	0.0325	100	3.65	1.11

SR16	RG1	J6	0.0325	100	3.65	1.04
SR17	RG1	J7	0.0325	100	3.65	0.44
SR18	RG1	J8	0.0325	100	3.65	0.44
SR19	RG1	J9	0.0325	100	3.65	1.92
SR20	RG1	J10	0.0325	100	3.65	1.92
SR21	RG1	J11	0.0325	100	3.65	2.02
SR22	RG1	J12	0.0325	100	3.65	2.02
SR00	RG1	J13	0.0325	100	3.65	1.94
SR01	RG1	J14	0.0325	100	3.65	1.94
1	RG1	J13	0.0325	100	3.65	1.98
2	RG1	J14	0.0325	100	3.65	1.94

***INSERT SUBCATCHMENT DATA BELOW*:**

[SUBAREAS]

Scatc	N-Imp	N-Perv	S-Imp	S-Perv	%Zero	RouteTo
K11	0.017	0.2	0.5	2	100	OUTLET
K12	0.017	0.2	0.5	2	100	OUTLET
K13	0.017	0.2	0.5	2	100	OUTLET
K14	0.017	0.2	0.5	2	100	OUTLET
K15	0.017	0.2	0.5	2	100	OUTLET
K16	0.017	0.2	0.5	2	100	OUTLET
K17	0.017	0.2	0.5	2	100	OUTLET
K18	0.017	0.2	0.5	2	100	OUTLET
K19	0.017	0.2	0.5	2	100	OUTLET
K20	0.017	0.2	0.5	2	100	OUTLET
K21	0.017	0.2	0.5	2	100	OUTLET
K22	0.017	0.2	0.5	2	100	OUTLET
KR11	0.017	0.2	0.5	2	100	OUTLET
KR12	0.017	0.2	0.5	2	100	OUTLET
KR13	0.017	0.2	0.5	2	100	OUTLET
KR14	0.017	0.2	0.5	2	100	OUTLET
KR15	0.017	0.2	0.5	2	100	OUTLET
KR16	0.017	0.2	0.5	2	100	OUTLET
KR17	0.017	0.2	0.5	2	100	OUTLET
KR18	0.017	0.2	0.5	2	100	OUTLET
KR19	0.017	0.2	0.5	2	100	OUTLET
KR20	0.017	0.2	0.5	2	100	OUTLET
KR21	0.017	0.2	0.5	2	100	OUTLET
KR22	0.017	0.2	0.5	2	100	OUTLET
KR00	0.017	0.2	0.5	2	100	OUTLET
KR01	0.017	0.2	0.5	2	100	OUTLET
R1	0.017	0.2	0.5	2	100	OUTLET
R2	0.017	0.2	0.5	2	100	OUTLET
R4	0.017	0.2	0.5	2	100	OUTLET
R3	0.017	0.2	0.5	2	100	OUTLET
R5	0.017	0.2	0.5	2	100	OUTLET
S11	0.017	0.2	0.5	2	100	OUTLET
S12	0.017	0.2	0.5	2	100	OUTLET
S13	0.017	0.2	0.5	2	100	OUTLET
S14	0.017	0.2	0.5	2	100	OUTLET
S15	0.017	0.2	0.5	2	100	OUTLET
S16	0.017	0.2	0.5	2	100	OUTLET
S17	0.017	0.2	0.5	2	100	OUTLET
S18	0.017	0.2	0.5	2	100	OUTLET
S19	0.017	0.2	0.5	2	100	OUTLET
S20	0.017	0.2	0.5	2	100	OUTLET

S21	0.017	0.2	0.5	2	100	OUTLET
S22	0.017	0.2	0.5	2	100	OUTLET
S27	0.017	0.2	0.5	2	100	OUTLET
S28	0.017	0.2	0.5	2	100	OUTLET
S29	0.017	0.2	0.5	2	100	OUTLET
S30	0.017	0.2	0.5	2	100	OUTLET
SR11	0.017	0.2	0.5	2	100	OUTLET
SR12	0.017	0.2	0.5	2	100	OUTLET
SR13	0.017	0.2	0.5	2	100	OUTLET
SR14	0.017	0.2	0.5	2	100	OUTLET
SR15	0.017	0.2	0.5	2	100	OUTLET
SR16	0.017	0.2	0.5	2	100	OUTLET
SR17	0.017	0.2	0.5	2	100	OUTLET
SR18	0.017	0.2	0.5	2	100	OUTLET
SR19	0.017	0.2	0.5	2	100	OUTLET
SR20	0.017	0.2	0.5	2	100	OUTLET
SR21	0.017	0.2	0.5	2	100	OUTLET
SR22	0.017	0.2	0.5	2	100	OUTLET
SR00	0.017	0.2	0.5	2	100	OUTLET
SR01	0.017	0.2	0.5	2	100	OUTLET
1	0.017	0.2	0.5	2	100	OUTLET
2	0.017	0.2	0.5	2	100	OUTLET

***INSERT JUNCTION DATA BELOW*:**
[JUNCTIONS]

Name	Elevation	Mxdp	Inid	SurDp	Aponded
J1	326.81	3.5	0	0	50
J2	325.1	3.24	0	0	50
J3	324.96	3	0	0	50
J4	323.78	3.36	0	0	50
J5	323.63	3.2	0	0	50
J6	323.28	3.41	0	0	50
J7	322.923 3.46	0	0	50	
J8	322.56	3.16	0	0	50
J9	321.05	3.16	0	0	50
J10	319.5	3.185	0	0	50
J11	317.9	3.24	0	0	50
J12	316.69	3	0	0	50
J13	332.39	3.23	0	0	50
J14	328.29	3.18	0	0	50

[OUTFALLS]

Name	Elevation	Type	Stage
O1	313.944 FREE	NO	

***INSERT CONDUIT DATA BELOW*:**
[CONDUITS]

Name	From	To	Length	‘n’	InOff	OutOf
C00	J13	J14	85.33	0.017	0	0.1524
C000	J14	J1	85.33	0.017	0	0.0762
C1	J1	J2	85.33	0.017	0	0
C2	J2	J3	85.33	0.017	0	0.0762
C3	J3	J4	85.33	0.017	0	0.1524
C4	J4	J5	85.33	0.017	0	0
C5	J5	J6	85.33	0.017	0	0
C6	J6	J7	85.33	0.017	0	0

C7	J7	J8	85.33	0.017	0	0
C8	J8	J9	85.33	0.017	0	0
C9	J9	J10	85.33	0.017	0	0
C10	J10	J11	85.33	0.017	0	0
C11	J11	J12	85.33	0.017	0	0
C12	J12	O1	10.59	0.017	0	0

INSERT CONDUIT GEOMETRY DATA BELOW:

[XSECTIONS]

Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels
C00	CIRCULAR	0.3048	0	0	0	1
C000	CIRCULAR	0.4572	0	0	0	1
C1	CIRCULAR	0.5334	0	0	0	1
C2	CIRCULAR	0.5334	0	0	0	1
C3	CIRCULAR	0.6096	0	0	0	1
C4	CIRCULAR	0.762	0	0	0	1
C5	CIRCULAR	0.762	0	0	0	1
C6	CIRCULAR	0.762	0	0	0	1
C7	CIRCULAR	0.762	0	0	0	1
C8	CIRCULAR	0.762	0	0	0	1
C9	CIRCULAR	0.762	0	0	0	1
C10	CIRCULAR	0.762	0	0	0	1
C11	CIRCULAR	0.762	0	0	0	1
C12	CIRCULAR	0.762	0	0	0	1

(2) Revised Subcatchment Conceptualization

NOTE: The input file runs for 1-year storm event. To model for all events in a single input file, change the '[RAINGAGES]' for each design storm, and substitute the appropriate 'TIMESERIES'.

[TITLE]	
Project	Title/Notes
[OPTIONS]	
Option	Value
FLOW_UNITS	CMS
INFILTRATION	GREEN_AMPT
FLOW_ROUTING	DYNWAVE
LINK_OFFSETS	DEPTH
MIN_SLOPE	0
ALLOW_PONDING	YES
SKIP_STEADY_STATE	NO
START_DATE	10/4/2016
START_TIME	0:00:00
REPORT_START_DATE	10/4/2016
REPORT_START_TIME	0:00:00
END_DATE	10/5/2016
END_TIME	4:00:00
SWEEP_START	1-Jan
SWEEP_END	31-Dec
DRY_DAYS	0
REPORT_STEP	0:05:00
WET_STEP	0:00:01
DRY_STEP	1:00:00
ROUTING_STEP	0:00:01
INERTIAL_DAMPING	PARTIAL

NORMAL_FLOW_LIMITED	BOTH
FORCE_MAIN_EQUATION	H-W
VARIABLE_STEP	0.75
LENGTHENING_STEP	0
MIN_SURFAREA	1.14
MAX_TRIALS	8
HEAD_TOLERANCE	0.0015
SYS_FLOW_TOL	5
LAT_FLOW_TOL	5
MINIMUM_STEP	0.5
THREADS	1

***INSERT RAINGAGE DATA BELOW*:**

[RAINGAGES]

Name	Format	Interval	SCF	Source
RG10	INTENSITY	0:05	1.0	TIMESERIES triangular_1hr_1yr

INSERT SUBCATCHMENT DATA BELOW:

[SUBCATCHMENTS]

Name	RainGage	Outlet	Area	%Imperv	Width	%slope
Apron1	RG10	Half_street1	0.011	100	21.3	3
Apron11	RG10	Half_street11	0.011	100	21.3	3
Apron12	RG10	Half_street12	0.011	100	21.3	3
Apron13	RG10	Half_street13	0.011	100	21.3	3
Apron14	RG10	Half_street14	0.022	100	42.7	3
Apron15	RG10	Half_street15	0.011	100	21.3	3
Apron16	RG10	Half_street16	0.022	100	42.7	3
Apron17	RG10	Half_street17	0.022	100	42.7	3
Apron18	RG10	Half_street18	0.022	100	42.7	3
Apron19	RG10	Half_street19	0.022	100	42.7	3
Apron2	RG10	Half_street2	0.011	100	21.3	3
Apron3	RG10	Half_street3	0.011	100	21.3	3
Apron4	RG10	Half_street4	0.022	100	42.7	3
Apron5	RG10	Half_street5	0.011	100	21.3	3
Apron6	RG10	Half_street6	0.022	100	42.7	3
Apron7	RG10	Half_street7	0.022	100	42.7	3
Apron8	RG10	Half_street8	0.022	100	42.7	3
Apron9	RG10	Half_street9	0.022	100	42.7	3
Driveway1	RG10	Apron1	0.042	100	17.1	3
Driveway11	RG10	Apron11	0.042	100	17.1	3
Driveway12	RG10	Apron12	0.042	100	17.1	3
Driveway13	RG10	Apron13	0.042	100	17.1	3
Driveway14	RG10	Apron14	0.083	100	34.1	3
Driveway15	RG10	Apron15	0.042	100	17.1	3
Driveway16	RG10	Apron16	0.083	100	34.1	3
Driveway17	RG10	Apron17	0.083	100	34.1	3
Driveway18	RG10	Apron18	0.083	100	34.1	3
Driveway19	RG10	Apron19	0.083	100	34.1	3
Driveway2	RG10	Apron2	0.042	100	17.1	3
Driveway3	RG10	Apron3	0.042	100	17.1	3
Driveway4	RG10	Apron4	0.083	100	34.1	3
Driveway5	RG10	Apron5	0.042	100	17.1	3
Driveway6	RG10	Apron6	0.083	100	34.1	3

Driveway7	RG10	Apron7	0.083	100	34.1	3
Driveway8	RG10	Apron8	0.083	100	34.1	3
Driveway9	RG10	Apron9	0.083	100	34.1	3
Half_street1	RG10	J1	0.033	100	3.65	3.86
Half_street11	RG10	U1	0.033	100	3.65	3.86
Half_street12	RG10	u3	0.033	100	3.65	4.84
Half_Street13	RG10	U5	0.033	100	3.65	1.74
Half_street14	RG10	U7	0.065	100	3.65	1.11
Half_street15	RG10	U9	0.033	100	3.65	1.04
Half_street16	RG10	U11	0.065	100	3.65	0.44
Half_street17	RG10	U13	0.065	100	3.65	1.92
Half_street18	RG10	U15	0.065	100	3.65	2.02
Half_street19	RG10	U17	0.065	100	3.65	1.94
Half_street2	RG10	J3	0.033	100	3.65	4.84
Half_Street3	RG10	J5	0.033	100	3.65	1.74
Half_street4	RG10	J7	0.065	100	3.65	1.11
Half_street5	RG10	J9	0.033	100	3.65	1.04
Half_street6	RG10	J11	0.065	100	3.65	0.44
Half_street7	RG10	J13	0.07	100	3.65	1.92
Half_street8	RG10	J15	0.065	100	3.65	2.02
Half_street9	RG10	J17	0.065	100	3.65	1.94
House&Garage1	RG10	1-Jun	0.083	100	63	100
House&Garage11	RG10	1-Jun	0.083	100	63	100
House&Garage12	RG10	2-Jun	0.083	100	126	100
House&Garage13	RG10	3-Jun	0.083	100	126	100
House&Garage14	RG10	4-Jun	0.16	100	126	100
House&Garage15	RG10	5-Jun	0.083	100	63	100
House&Garage16	RG10	6-Jun	0.16	100	126	100
House&Garage17	RG10	7-Jun	0.16	100	126	100
House&Garage18	RG10	8-Jun	0.16	100	126	100
House&Garage19	RG10	9-Jun	0.16	100	126	100
House&Garage2	RG10	2-Jun	0.083	100	63	100
House&Garage3	RG10	3-Jun	0.083	100	63	100
House&Garage4	RG10	4-Jun	0.16	100	126	100
House&Garage5	RG10	5-Jun	0.083	100	63	100
House&Garage6	RG10	6-Jun	0.16	100	126	100
House&Garage7	RG10	7-Jun	0.16	100	126	100
House&Garage8	RG10	8-Jun	0.16	100	126	100
House&Garage9	RG10	9-Jun	0.16	100	126	100
Sidewalk1	RG10	Tree_lawn1	0.011	100	85.3	3
Sidewalk11	RG10	Tree_lawn11	0.01	100	85.3	3
Sidewalk12	RG10	Tree_lawn12	0.01	100	85.3	3
Sidewalk13	RG10	Tree_lawn13	0.01	100	85.3	3
Sidewalk14	RG10	Tree_lawn14	0.021	100	171	3
Sidewalk15	RG10	Tree_lawn15	0.01	100	85.3	3
Sidewalk16	RG10	Tree_lawn16	0.021	100	171	3
Sidewalk17	RG10	Tree_lawn17	0.021	100	171	3
Sidewalk18	RG10	Tree_lawn18	0.021	100	171	3
Sidewalk19	RG10	Tree_lawn19	0.021	100	171	3
Sidewalk2	RG10	Tree_lawn2	0.01	100	85.3	3
Sidewalk3	RG10	Tree_lawn3	0.01	100	85.3	3
Sidewalk4	RG10	Tree_lawn4	0.021	100	171	3
Sidewalk5	RG10	Tree_lawn5	0.01	100	85.3	3
Sidewalk6	RG10	Tree_lawn6	0.021	100	171	3

Sidewalk7	RG10	Tree_lawn7	0.021	100	171	3
Sidewalk8	RG10	Tree_lawn8	0.021	100	171	3
Sidewalk9	RG10	Tree_lawn9	0.021	100	171	3
SR1	RG10	2-Jun	0.065	100	8	2
SR2	RG10	6-Jun	0.065	100	8	2
SR3	RG10	7-Jun	0.065	100	8	2
SR4	RG10	6-Jun	0.065	100	8	2
SR5	RG10	7-Jun	0.065	100	8	2
Tree_lawn1	RG10	Half_street1	0.043	0	68.2	3
Tree_lawn11	RG10	Half_street11	0.043	0	68.2	3
Tree_lawn12	RG10	Half_street12	0.043	0	68.2	3
Tree_lawn13	RG10	Half_street13	0.043	0	68.2	3
Tree_lawn14	RG10	Half_street14	0.085	0	136	3
Tree_lawn15	RG10	Half_street15	0.043	0	68.2	3
Tree_lawn16	RG10	Half_street16	0.085	0	136	3
Tree_lawn17	RG10	Half_street17	0.085	0	136	3
Tree_lawn18	RG10	Half_street18	0.085	0	136	3
Tree_lawn19	RG10	Half_street19	0.085	0	136	3
Tree_lawn2	RG10	Half_street2	0.043	0	68.2	3
Tree_lawn3	RG10	Half_street3	0.043	0	68.2	3
Tree_lawn4	RG10	Half_street4	0.085	0	136	3
Tree_lawn5	RG10	Half_street5	0.043	0	68.2	3
Tree_lawn6	RG10	Half_street6	0.085	0	136	3
Tree_lawn7	RG10	Half_street7	0.085	0	136	3
Tree_lawn8	RG10	Half_street8	0.085	0	136	3
Tree_lawn9	RG10	Half_street9	0.085	0	136	3
Yard1	RG10	Sidewalk1	0.198	0	68.3	3
Yard11	RG10	Sidewalk11	0.198	0	68.3	3
Yard12	RG10	Sidewalk12	0.198	0	68.3	3
Yard13	RG10	Sidewalk13	0.198	0	68.3	3
Yard14	RG10	Sidewalk14	0.4	0	137	3
Yard15	RG10	Sidewalk15	0.198	0	68.3	3
Yard16	RG10	Sidewalk16	0.395	0	137	3
Yard17	RG10	Sidewalk17	0.395	0	137	3
Yard18	RG10	Sidewalk18	0.395	0	137	3
Yard19	RG10	Sidewalk19	0.395	0	137	3
Yard2	RG10	Sidewalk2	0.198	0	68.3	3
Yard3	RG10	Sidewalk3	0.198	0	68.3	3
Yard4	RG10	Sidewalk4	0.395	0	137	3
Yard5	RG10	Sidewalk5	0.198	0	68.3	3
Yard6	RG10	Sidewalk6	0.395	0	137	3
Yard7	RG10	Sidewalk7	0.395	0	137	3
Yard8	RG10	Sidewalk8	0.395	0	137	3
Yard9	RG10	Sidewalk9	0.395	0	137	3

***INSERT SUBCATCHMENT DATA BELOW:**

[SUBAREAS]

Subcatchment	NImp	NPer	SImp	SPerv	PctZero	RouteTo
Apron1	0.017	0.2	0.5	2	100	OUTLET
Apron11	0.017	0.2	0.5	2	100	OUTLET
Apron12	0.017	0.2	0.5	2	100	OUTLET
Apron13	0.017	0.2	0.5	2	100	OUTLET
Apron14	0.017	0.2	0.5	2	100	OUTLET
Apron15	0.017	0.2	0.5	2	100	OUTLET

Apron16	0.017	0.2	0.5	2	100	OUTLET
Apron17	0.017	0.2	0.5	2	100	OUTLET
Apron18	0.017	0.2	0.5	2	100	OUTLET
Apron19	0.017	0.2	0.5	2	100	OUTLET
Apron2	0.017	0.2	0.5	2	100	OUTLET
Apron3	0.017	0.2	0.5	2	100	OUTLET
Apron4	0.017	0.2	0.5	2	100	OUTLET
Apron5	0.017	0.2	0.5	2	100	OUTLET
Apron6	0.017	0.2	0.5	2	100	OUTLET
Apron7	0.017	0.2	0.5	2	100	OUTLET
Apron8	0.017	0.2	0.5	2	100	OUTLET
Apron9	0.017	0.2	0.5	2	100	OUTLET
Driveway1	0.017	0.2	0.5	2	100	OUTLET
Driveway11	0.017	0.2	0.5	2	100	OUTLET
Driveway12	0.017	0.2	0.5	2	100	OUTLET
Driveway13	0.017	0.2	0.5	2	100	OUTLET
Driveway14	0.017	0.2	0.5	2	100	OUTLET
Driveway15	0.017	0.2	0.5	2	100	OUTLET
Driveway16	0.017	0.2	0.5	2	100	OUTLET
Driveway17	0.017	0.2	0.5	2	100	OUTLET
Driveway18	0.017	0.2	0.5	2	100	OUTLET
Driveway19	0.017	0.2	0.5	2	100	OUTLET
Driveway2	0.017	0.2	0.5	2	100	OUTLET
Driveway3	0.017	0.2	0.5	2	100	OUTLET
Driveway4	0.017	0.2	0.5	2	100	OUTLET
Driveway5	0.017	0.2	0.5	2	100	OUTLET
Driveway6	0.017	0.2	0.5	2	100	OUTLET
Driveway7	0.017	0.2	0.5	2	100	OUTLET
Driveway8	0.017	0.2	0.5	2	100	OUTLET
Driveway9	0.017	0.2	0.5	2	100	OUTLET
Half_street1	0.017	0.2	0.5	2	100	OUTLET
Half_street11	0.017	0.2	0.5	2	100	OUTLET
Half_street12	0.017	0.2	0.5	2	100	OUTLET
Half_Street13	0.017	0.2	0.5	2	100	OUTLET
Half_street14	0.017	0.2	0.5	2	100	OUTLET
Half_street15	0.017	0.2	0.5	2	100	OUTLET
Half_street16	0.017	0.2	0.5	2	100	OUTLET
Half_street17	0.017	0.2	0.5	2	100	OUTLET
Half_street18	0.017	0.2	0.5	2	100	OUTLET
Half_street19	0.017	0.2	0.5	2	100	OUTLET
Half_street2	0.017	0.2	0.5	2	100	OUTLET
Half_Street3	0.017	0.2	0.5	2	100	OUTLET
Half_street4	0.017	0.2	0.5	2	100	OUTLET
Half_street5	0.017	0.2	0.5	2	100	OUTLET
Half_street6	0.017	0.2	0.5	2	100	OUTLET
Half_street7	0.017	0.2	0.5	2	100	OUTLET
Half_street8	0.017	0.2	0.5	2	100	OUTLET
Half_street9	0.017	0.2	0.5	2	100	OUTLET
House&Garage1	0.017	0.2	0.01	2	100	OUTLET
House&Garage11	0.017	0.2	0.01	2	100	OUTLET
House&Garage12	0.017	0.2	0.01	2	100	OUTLET
House&Garage13	0.017	0.2	0.01	2	100	OUTLET
House&Garage14	0.017	0.2	0.01	2	100	OUTLET
House&Garage15	0.017	0.2	0.01	2	100	OUTLET
House&Garage16	0.017	0.2	0.01	2	100	OUTLET
House&Garage17	0.017	0.2	0.01	2	100	OUTLET

House&Garage18	0.017	0.2	0.01	2	100	OUTLET
House&Garage19	0.017	0.2	0.01	2	100	OUTLET
House&Garage2	0.017	0.2	0.01	2	100	OUTLET
House&Garage3	0.017	0.2	0.01	2	100	OUTLET
House&Garage4	0.017	0.2	0.01	2	100	OUTLET
House&Garage5	0.017	0.2	0.01	2	100	OUTLET
House&Garage6	0.017	0.2	0.01	2	100	OUTLET
House&Garage7	0.017	0.2	0.01	2	100	OUTLET
House&Garage8	0.017	0.2	0.01	2	100	OUTLET
House&Garage9	0.017	0.2	0.01	2	100	OUTLET
Sidewalk1	0.017	0.2	0.5	2	100	OUTLET
Sidewalk11	0.017	0.2	0.5	2	100	OUTLET
Sidewalk12	0.017	0.2	0.5	2	100	OUTLET
Sidewalk13	0.017	0.2	0.5	2	100	OUTLET
Sidewalk14	0.017	0.2	0.5	2	100	OUTLET
Sidewalk15	0.017	0.2	0.5	2	100	OUTLET
Sidewalk16	0.017	0.2	0.5	2	100	OUTLET
Sidewalk17	0.017	0.2	0.5	2	100	OUTLET
Sidewalk18	0.017	0.2	0.5	2	100	OUTLET
Sidewalk19	0.017	0.2	0.5	2	100	OUTLET
Sidewalk2	0.017	0.2	0.5	2	100	OUTLET
Sidewalk3	0.017	0.2	0.5	2	100	OUTLET
Sidewalk4	0.017	0.2	0.5	2	100	OUTLET
Sidewalk5	0.017	0.2	0.5	2	100	OUTLET
Sidewalk6	0.017	0.2	0.5	2	100	OUTLET
Sidewalk7	0.017	0.2	0.5	2	100	OUTLET
Sidewalk8	0.017	0.2	0.5	2	100	OUTLET
Sidewalk9	0.017	0.2	0.5	2	100	OUTLET
SR1	0.017	0.2	0.5	2	100	OUTLET
SR2	0.017	0.2	0.5	2	100	OUTLET
SR3	0.017	0.2	0.5	2	100	OUTLET
SR4	0.017	0.2	0.5	2	100	OUTLET
SR5	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn1	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn11	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn12	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn13	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn14	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn15	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn16	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn17	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn18	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn19	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn2	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn3	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn4	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn5	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn6	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn7	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn8	0.017	0.2	0.5	2	100	OUTLET
Tree_lawn9	0.017	0.2	0.5	2	100	OUTLET
Yard1	0.017	0.2	0.5	2	100	OUTLET
Yard11	0.017	0.2	0.5	2	100	OUTLET
Yard12	0.017	0.2	0.5	2	100	OUTLET
Yard13	0.017	0.2	0.5	2	100	OUTLET
Yard14	0.017	0.2	0.5	2	100	OUTLET

Yard15	0.017	0.2	0.5	2	100	OUTLET
Yard16	0.017	0.2	0.5	2	100	OUTLET
Yard17	0.017	0.2	0.5	2	100	OUTLET
Yard18	0.017	0.2	0.5	2	100	OUTLET
Yard19	0.017	0.2	0.5	2	100	OUTLET
Yard2	0.017	0.2	0.5	2	100	OUTLET
Yard3	0.017	0.2	0.5	2	100	OUTLET
Yard4	0.017	0.2	0.5	2	100	OUTLET
Yard5	0.017	0.2	0.5	2	100	OUTLET
Yard6	0.017	0.2	0.5	2	100	OUTLET
Yard7	0.017	0.2	0.5	2	100	OUTLET
Yard8	0.017	0.2	0.5	2	100	OUTLET
Yard9	0.017	0.2	0.5	2	100	OUTLET

***INSERT JUNCTION DATA BELOW:**

[JUNCTIONS]

Name	Elevation	MaxDepth	InitDepth	SurDepth	Aponded
1-Jun	332.39	3.23	0	0	50
2-Jun	328.29	3.18	0	0	50
3-Jun	326.81	3.5	0	0	50
4-Jun	324.96	3	0	0	50
5-Jun	323.78	3.36	0	0	50
6-Jun	323.28	3.41	0	0	50
7-Jun	322.56	3.16	0	0	50
8-Jun	319.5	3.185	0	0	50
9-Jun	316.69	3	0	0	50
J1	334.39	1.23	0	0	50
J10	325.765	1.26	0	0	50
J11	325.58	1.41	0	0	50
J12	325.565	1.41	0	0	50
J13	324.56	1.16	0	0	50
J14	324.545	1.16	0	0	50
J15	321.5	1.185	0	0	50
J16	321.485	1.185	0	0	50
J17	318.69	1	0	0	50
J2	334.375	1.23	0	0	50
J3	330.29	1.18	0	0	50
J4	330.275	1.18	0	0	50
J5	328.81	1.5	0	0	50
J6	328.795	1.5	0	0	50
J7	326.96	1.24	0	0	50
J8	326.945	1.24	0	0	50
J9	325.78	1.26	0	0	50
U1	334.39	1.23	0	0	50
U10	325.765	1.26	0	0	50
U11	325.58	1.41	0	0	50
U12	325.565	1.41	0	0	50
U13	324.56	1.16	0	0	50
U14	324.545	1.16	0	0	50
U15	321.5	1.185	0	0	50
U16	321.485	1.185	0	0	50
U17	318.69	1	0	0	50
U2	334.375	1.23	0	0	50
U3	330.29	1.18	0	0	50
U4	330.275	1.18	0	0	50
U5	328.81	1.5	0	0	50

U6	328.795	1.5	0	0	50
U7	326.96	1.24	0	0	50
U8	326.945	1.24	0	0	50
U9	325.78	1.26	0	0	50

[OUTFALLS]

Name	Elevation	Type	Stage
OUT1	313.944	FREE	NO

INSERT CONDUIT DATA BELOW:

[CONDUITS]

Name	FromNode	ToNode	Length	Roughness	InOffset	OutOffset
C1	J1	J2	2	0	0	0
C10	J10	J11	168.7	0	0.02	0
C11	J11	J12	2	0	0	0
C12	J12	J13	168.7	0	0.02	0
C13	J13	J14	2	0	0	0
C14	J14	J15	168.7	0	0.02	0
C15	J15	J16	2	0	0	0
C16	J16	J17	168.7	0	0.02	0
C2	J2	J3	83.33	0	0.02	0
C3	J3	J4	2	0	0	0
C4	J4	J5	83.33	0	0.02	0
C5	J5	J6	2	0	0	0
C6	J6	J7	168.7	0	0.02	0
C7	J7	J8	2	0	0	0
C8	J8	J9	83.33	0	0.02	0
C9	J9	J10	2	0	0	0
CO1	1-Jun	2-Jun	85.33	0	0	0.1524
CO2	2-Jun	3-Jun	85.33	0	0	0.0762
CO3	3-Jun	4-Jun	170.7	0	0	0.1524
CO4	4-Jun	5-Jun	85.33	0	0	0.1524
CO5	5-Jun	6-Jun	170.7	0	0	0
CO6	6-Jun	7-Jun	170.7	0	0	0
CO7	7-Jun	8-Jun	170.7	0	0	0
CO8	8-Jun	9-Jun	170.7	0	0	0
CO9	9-Jun	OUT1	10.59	0	0	0
N1	U1	U2	2	0	0	0
N10	U10	U11	83.33	0	0.02	0
N11	U11	U12	2	0	0	0
N12	U12	U13	168.7	0	0.02	0
N13	U13	U14	2	0	0	0
N14	U14	U15	168.7	0	0.02	0
N15	U15	U16	2	0	0	0
N16	U16	U17	168.7	0	0.02	0
N2	U2	U3	83.33	0	0.02	0
N3	U3	U4	2	0	0	0
N4	U4	U5	83.33	0	0.02	0
N5	U5	U6	2	0	0	0
N6	U6	U7	168.7	0	0.02	0
N7	U7	U8	2	0	0	0
N8	U8	U9	83.33	0	0.02	0
N9	U9	U10	2	0	0	0
C17	J17	9-Jun	11	0	0	0
C18	U17	9-Jun	11	0	0	0

[ORIFICES]

Name	FromNode	ToNode	Type	Offset	Qcoeff	Gated
O1	J2	1-Jun	BOTTOM	0	0.65	NO
O2	J4	2-Jun	BOTTOM	0	0.65	NO
O3	J6	3-Jun	BOTTOM	0	0.65	NO
O4	J8	4-Jun	BOTTOM	0	0.65	NO
O5	J10	5-Jun	BOTTOM	0	0.65	NO
O6	J12	6-Jun	BOTTOM	0	0.65	NO
O7	J14	7-Jun	BOTTOM	0	0.65	NO
O8	J16	8-Jun	BOTTOM	0	0.65	NO
O9	J17	9-Jun	BOTTOM	0	0.65	NO
R1	U2	1-Jun	BOTTOM	0	0.65	NO
R2	U4	2-Jun	BOTTOM	0	0.65	NO
R3	U6	3-Jun	BOTTOM	0	0.65	NO
R4	U8	4-Jun	BOTTOM	0	0.65	NO
R5	U10	5-Jun	BOTTOM	0	0.65	NO
R6	U12	6-Jun	BOTTOM	0	0.65	NO
R7	U14	7-Jun	BOTTOM	0	0.65	NO
R8	U16	8-Jun	BOTTOM	0	0.65	NO
R9	U17	9-Jun	BOTTOM	0	0.65	NO

****INSERT CONDUIT GEOMETRY DATA BELOW:***

[XSECTIONS]

Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels
C1	IRREGULAR	Half_St_Conduit	0	0	0	
C10	IRREGULAR	Half_St_Conduit	0	0	0	1
C11	IRREGULAR	Half_St_Conduit	0	0	0	1
C12	IRREGULAR	Half_St_Conduit	0	0	0	1
C13	IRREGULAR	Half_St_Conduit	0	0	0	1
C14	IRREGULAR	Half_St_Conduit	0	0	0	1
C15	IRREGULAR	Half_St_Conduit	0	0	0	1
C16	IRREGULAR	Half_St_Conduit	0	0	0	1
C2	IRREGULAR	Half_St_Conduit	0	0	0	1
C3	IRREGULAR	Half_St_Conduit	0	0	0	1
C4	IRREGULAR	Half_St_Conduit	0	0	0	1
C5	IRREGULAR	Half_St_Conduit	0	0	0	1
C6	IRREGULAR	Half_St_Conduit	0	0	0	1
C7	IRREGULAR	Half_St_Conduit	0	0	0	1
C8	IRREGULAR	Half_St_Conduit	0	0	0	1
C9	IRREGULAR	Half_St_Conduit	0	0	0	1
CO1	CIRCULAR	0.3048	0	0	0	1
CO2	CIRCULAR	0.4572	0	0	0	1
CO3	CIRCULAR	0.5334	0	0	0	1
CO4	CIRCULAR	0.6096	0	0	0	1
CO5	CIRCULAR	0.762	0	0	0	1
CO6	CIRCULAR	0.762	0	0	0	1
CO7	CIRCULAR	0.762	0	0	0	1
CO8	CIRCULAR	0.762	0	0	0	1
CO9	CIRCULAR	0.762	0	0	0	1
N1	IRREGULAR	Half_St_Conduit	0	0	0	1
N10	IRREGULAR	Half_St_Conduit	0	0	0	1
N11	IRREGULAR	Half_St_Conduit	0	0	0	1

N12	IRREGULAR	Half_St_Conduit	0	0	0	1
N13	IRREGULAR	Half_St_Conduit	0	0	0	1
N14	IRREGULAR	Half_St_Conduit	0	0	0	1
N15	IRREGULAR	Half_St_Conduit	0	0	0	1
N16	IRREGULAR	Half_St_Conduit	0	0	0	1
N2	IRREGULAR	Half_St_Conduit	0	0	0	1
N3	IRREGULAR	Half_St_Conduit	0	0	0	1
N4	IRREGULAR	Half_St_Conduit	0	0	0	1
N5	IRREGULAR	Half_St_Conduit	0	0	0	1
N6	IRREGULAR	Half_St_Conduit	0	0	0	1
N7	IRREGULAR	Half_St_Conduit	0	0	0	1
N8	IRREGULAR	Half_St_Conduit	0	0	0	1
N9	IRREGULAR	Half_St_Conduit	0	0	0	1
C17	CIRCULAR	0.762	0	0	0	1
C18	CIRCULAR	0.762	0	0	0	1
O1	CIRCULAR	0.1524	0	0	0	1
O2	CIRCULAR	0.1524	0	0	0	
O3	CIRCULAR	0.1524	0	0	0	
O4	CIRCULAR	0.1524	0	0	0	
O5	CIRCULAR	0.1524	0	0	0	
O6	CIRCULAR	0.1524	0	0	0	
O7	CIRCULAR	0.1524	0	0	0	
O8	CIRCULAR	0.1524	0	0	0	
O9	CIRCULAR	0.1524	0	0	0	
R1	CIRCULAR	0.1524	0	0	0	
R2	CIRCULAR	0.1524	0	0	0	
R3	CIRCULAR	0.1524	0	0	0	
R4	CIRCULAR	0.1524	0	0	0	
R5	CIRCULAR	0.1524	0	0	0	
R6	CIRCULAR	0.1524	0	0	0	
R7	CIRCULAR	0.1524	0	0	0	
R8	CIRCULAR	0.1524	0	0	0	
R9	CIRCULAR	0.1524	0	0	0	

[TRANSECTS]

NC	0.015	0.015	0.015				
X1	Half_St_Con	4	0	0	0	0	0
GR	1	0	0	0	0.24	3.65	

C. SWMM OUTPUT FILE

(1) Conventional Subcatchment Conceptualization

Analysis	Options
Flow Units	CMS
Process Models	
Rainfall/Runoff	YES
RDII	NO
Snowmelt	NO
Groundwater	NO
FlowRouting	YES
PondingAllowed	YES
WaterQuality	NO
Infiltration Method	Green_Ampt
Flow Routing Method	DYNWAVE
Starting Date	4/30/2016 0:00:00
Ending Date	5/2/201604:00:00
Antecedent Dry Days	0
Report Time Step	0:01:00
Wet Time Step	0:05:00
Dry Time Step	6:00:00
Routing Time Step	1sec
Variable Time Step	YES
Maximum Trials	8
Number of Threads	1
Head Tolerance	0.0015m

Runoff Quantity Continuity	Volume (hec-m)	Depth (mm)
Total Precipitation	0.3	24.997
Evaporation Loss	0	0
Infiltration Loss	0.143	11.93
SurfaceRunoff	0.158	13.178
Final Storage	0	0.001
Continuity Error (%)	-0.432	

Flow Routing Continuity	Volume (hec-m)	Volume 10^6ltr
Dry Weather Inflow	0	0
Wet Weather Inflow	0.158	1.58
Groundwater Inflow	0	0
RDII Inflow	0	0
External Inflow	0	0
External Outflow	0.158	1.58
Flooding Loss	0	0

Evaporation Loss	0	0
Exfiltration Loss	0	0
Initial Stored	0	0
Final Stored	0	0
Continuity Error (%)	0.005	

Time-Step Critical Elements
None

Highest Flow Instability Indexes
All links are stable

Routing Time Step Summary
Minimum Time Step : 0.660 sec
Average Time Step : 1.00 sec
Maximum Time Step : 1.00 sec
Percent in Steady State : 0.00
Average Iterations per Step: 2.00
Percent Not Converging : 0.00

Subcatchment Runoff Summary

Subcat	Total Precip mm	Total Runon mm	Total Evap mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6	Peak Runoff ltr	Runoff Coeff CMS
K11	25	0	0	12.9	12.22	0.05	0.02	0.489
K12	25	0	0	12.88	12.24	0.05	0.02	0.49
K13	25	0	0	13.3	11.81	0.05	0.02	0.472
K14	25	0	0	13.55	11.56	0.04	0.02	0.462
K15	25	0	0	13.55	11.56	0.04	0.02	0.462
K16	25	0	0	13.58	11.52	0.04	0.02	0.461
K17	25	0	0	14.06	11.03	0.04	0.02	0.441
K18	25	0	0	14.06	11.03	0.04	0.02	0.441
K19	25	0	0	13.24	11.86	0.05	0.02	0.474
K20	25	0	0	13.24	11.86	0.05	0.02	0.474
K21	25	0	0	13.22	11.88	0.05	0.02	0.475
K22	25	0	0	13.22	11.88	0.05	0.02	0.475
KR11	25	0	0	0	25.16	0.01	0	1.006
KR12	25	0	0	0	25.16	0.01	0	1.006
KR13	25	0	0	0	25.15	0.01	0	1.006
KR14	25	0	0	0	25.14	0.01	0	1.006
KR15	25	0	0	0	25.14	0.01	0	1.006
KR16	25	0	0	0	25.14	0.01	0	1.006
KR17	25	0	0	0	25.12	0.01	0	1.005
KR18	25	0	0	0	25.12	0.01	0	1.005
KR19	25	0	0	0	25.15	0.01	0	1.006
KR20	25	0	0	0	25.15	0.01	0	1.006
KR21	25	0	0	0	25.15	0.01	0	1.006
KR22	25	0	0	0	25.15	0.01	0	1.006
KR00	25	0	0	0	25.15	0.01	0	1.006
KR01	25	0	0	0	25.15	0.01	0	1.006
R1	25	0	0	0	25.15	0.02	0.01	1.006
R2	25	0	0	0	25.15	0.02	0.01	1.006
R4	25	0	0	0	25.15	0.02	0.01	1.006
R3	25	0	0	0	25.15	0.02	0.01	1.006
R5	25	0	0	0	25.15	0.02	0.01	1.006

S11		25	0	0	12.9	12.22	0.05	0.02	0.489
S12		25	0	0	12.88	12.24	0.05	0.02	0.49
S13		25	0	0	13.3	11.81	0.05	0.02	0.472
S14		25	0	0	13.55	11.56	0.04	0.02	0.462
S15		25	0	0	13.55	11.56	0.04	0.02	0.462
S16		25	0	0	13.58	11.52	0.04	0.02	0.461
S17		25	0	0	14.06	11.03	0.04	0.02	0.441
S18		25	0	0	14.06	11.03	0.04	0.02	0.441
S19		25	0	0	13.24	11.86	0.05	0.02	0.474
S20		25	0	0	13.24	11.86	0.05	0.02	0.474
S21		25	0	0	13.22	11.88	0.05	0.02	0.475
S22		25	0	0	13.22	11.88	0.05	0.02	0.475
S27		25	0	0	13.22	11.88	0.05	0.02	0.475
S28		25	0	0	13.22	11.88	0.05	0.02	0.475
S29		25	0	0	13.22	11.88	0.05	0.02	0.475
S30		25	0	0	13.22	11.88	0.05	0.02	0.475
SR11		25	0	0	0	25.16	0.01	0	1.006
SR12		25	0	0	0	25.16	0.01	0	1.006
SR13		25	0	0	0	25.15	0.01	0	1.006
SR14		25	0	0	0	25.14	0.01	0	1.006
SR15		25	0	0	0	25.14	0.01	0	1.006
SR16		25	0	0	0	25.14	0.01	0	1.006
SR17		25	0	0	0	25.12	0.01	0	1.005
SR18		25	0	0	0	25.12	0.01	0	1.005
SR19		25	0	0	0	25.15	0.01	0	1.006
SR20		25	0	0	0	25.15	0.01	0	1.006
SR21		25	0	0	0	25.15	0.01	0	1.006
SR22		25	0	0	0	25.15	0.01	0	1.006
SR00		25	0	0	0	25.15	0.01	0	1.006
SR01		25	0	0	0	25.15	0.01	0	1.006
	1	25	0	0	0	25.15	0.01	0	1.006
	2	25	0	0	0	25.15	0.01	0	1.006

Node Depth Summary

Node	Type	Avg Depth Meters	Max Depth Meters	Max HGL Meters	Timeof Occurence hr:min	Reported Max dep Meters
J1	JUNCTION	0	0.21	327.02	0:31	0.21
J2	JUNCTION	0.01	0.64	325.74	0:32	0.64
J3	JUNCTION	0.01	0.3	325.26	0:32	0.3
J4	JUNCTION	0.01	0.52	324.3	0:32	0.52
J5	JUNCTION	0.01	0.44	324.07	0:33	0.44
J6	JUNCTION	0.01	0.47	323.75	0:34	0.47
J7	JUNCTION	0.01	0.48	323.41	0:34	0.48
J8	JUNCTION	0.01	0.35	322.91	0:34	0.35
J9	JUNCTION	0.01	0.36	321.41	0:34	0.36
J10	JUNCTION	0.01	0.38	319.88	0:35	0.38
J11	JUNCTION	0.01	0.46	318.36	0:35	0.46
J12	JUNCTION	0	0.2	316.89	0:35	0.2
J13	JUNCTION	0	0.12	332.51	0:30	0.12
J14	JUNCTION	0	0.19	328.48	0:30	0.19
O1	OUTFALL	0	0.2	314.14	0:35	0.20

Node Inflow Summary

Node	Type	Max Lateral Inflow CMS	Max Total Inflow CMS	Total of Volume hr:min	Flow Max Volume 10^6	Inflow Error ltr	Inflow 10^6
J1	JUNCTION	0.05	0.16	0:31	0.11	0.357	-0.071
J2	JUNCTION	0.05	0.209	0:32	0.11	0.467	0.056
J3	JUNCTION	0.047	0.256	0:32	0.107	0.573	0.022
J4	JUNCTION	0.061	0.316	0:31	0.136	0.709	-0.026
J5	JUNCTION	0.046	0.361	0:32	0.105	0.814	0.009
J6	JUNCTION	0.045	0.406	0:33	0.104	0.918	-0.003
J7	JUNCTION	0.043	0.448	0:33	0.101	1.02	0.012
J8	JUNCTION	0.059	0.504	0:33	0.133	1.15	0.003
J9	JUNCTION	0.047	0.551	0:34	0.107	1.26	-0.001
J10	JUNCTION	0.047	0.598	0:34	0.107	1.37	-0.005
J11	JUNCTION	0.047	0.645	0:35	0.107	1.47	0.006
J12	JUNCTION	0.047	0.692	0:35	0.107	1.58	-0.004
J13	JUNCTION	0.051	0.051	0:30	0.115	0.115	-0.001
J14	JUNCTION	0.059	0.11	0:30	0.132	0.247	-0.003
O1	OUTFALL	0	0.692	0:35	0	1.58	0

Node Surcharge Summary

Surcharging occurs when water rises above the top of the highest conduit.

Node	Type	Hours Surcharged	Max. Height Above crown Meters	Min. Depth Below Rim Meters
J2	JUNCTION	0.33	0.109	2.598

Node Flooding Summary

No nodes were flooded.

Outfall Loading Summary

Outfall Node	Flow Freq Pcnt	Avg Flow CMS	Max Flow CMS	Total Volume 10^6
O1	15.07	0.055	0.692	1.58
System	15.07	0.055	0.692	1.58

Link Flow Summary

Link	Type	Maximum |Flow| CMS	Time of Occurrence days	hr:min	Max |Veloc| m/sec	Max/ Full Flow	Max/ Full Depth
C00	CONDUIT	0.051	0	0:30	2	0.31	0.38
C000	CONDUIT	0.11	0	0:30	1.65	0.38	0.43
C1	CONDUIT	0.16	0	0:31	0.96	0.33	0.7
C2	CONDUIT	0.209	0	0:32	1.11	2.23	0.79
C3	CONDUIT	0.256	0	0:32	1.63	0.48	0.54
C4	CONDUIT	0.316	0	0:32	1.05	0.85	0.63
C5	CONDUIT	0.361	0	0:33	1.27	0.63	0.6
C6	CONDUIT	0.405	0	0:34	1.34	0.71	0.63
C7	CONDUIT	0.448	0	0:34	1.76	0.77	0.55

C8	CONDUIT	0.504	0	0:34	2.42	0.43	0.47
C9	CONDUIT	0.551	0	0:34	2.51	0.46	0.49
C10	CONDUIT	0.598	0	0:35	2.32	0.49	0.55
C11	CONDUIT	0.645	0	0:35	3.38	0.61	0.44
C12	CONDUIT	0.692	0	0:35	7.21	0.15	0.26

Flow Classification Summary

		Fraction of Time in Flow Class								
Conduit	Adjusted /Actual Length	Dry	Up Dry	Down Dry	Sub Crit	Sup Crit	Up Crit	Down Crit	Norm Ltd	Inlet Ctrl
C00	1	0	0	0	0	0	0	1	0	0
C000	1	0	0	0	0	0	0	1	0	0
C1	1	0	0.35	0	0.65	0	0	0	1	0
C2	1	0	0	0	0	0	0	1	0	0
C3	1	0	0	0	0	0.01	0	0.99	0.01	0
C4	1	0	0	0	1	0	0	0	0.01	0
C5	1	0	0	0	1	0	0	0	0.96	0
C6	1	0	0	0	1	0	0	0	0.45	0
C7	1	0	0	0	0.99	0.01	0	0	0.55	0
C8	1	0	0	0	0.93	0.06	0	0	0.43	0
C9	1	0	0	0	0.93	0.07	0	0	0.96	0
C10	1	0	0	0	0.96	0.04	0	0	0.43	0
C11	1	0	0	0	0.88	0.11	0	0	0.64	0
C12	1	0	0	0	0.66	0.34	0	0	0.01	0

Conduit Surcharge Summary

	Both	Hours Full		Above Full	HoursCapacity
Conduit	Ends	Upstream	Downstream	Normal Flow	Limited
C1	0.01	0.01	0.33	0.01	0.01
C2	0.01	0.33	0.01	0.64	0.01

(2) Revised Subcatchment Conceptualization

Analysis	Options
Flow Units	CMS
Process Models	
Rainfall/Runoff	YES
RDII	NO
Snowmelt	NO
Groundwater	NO
Flow Routing	YES
Ponding Allowed	YES
Water Quality	NO
Infiltration Method	Green_Ampt
Flow Routing Method	DYNWAVE
Starting Date	10/4/2016 0:00:00
Ending Date	10/5/201604:00:00
Antecedent Dry Days	0
Report Time Step	0:05:00
Wet Time Step	0:00:01

Dry Time Step	1:00:00
Routing Time Step	1sec
Variable Time Step	YES
Maximum Trials	8
Number of Threads	1
Head Tolerance	0.0015m

Runoff Quantity Continuity	Volume (hec-m)	Depth (mm)
Total Precipitation	0.3	24.997
Evaporation Loss	0	0
Infiltration Loss	0.136	11.34
SurfaceRunoff	0.164	13.656
Final Storage	0	0.001
Continuity Error (%)	0	

Flow Routing Continuity	Volume (hec-m)	Volume 10^6ltr
Dry Weather Inflow	0	0
Wet Weather Inflow	0.164	1.638
Groundwater Inflow	0	0
RDII Inflow	0	0
External Inflow	0	0
External Outflow	0.164	1.638
Flooding Loss	0	0
Evaporation Loss	0	0
Exfiltration Loss	0	0
Initial Stored	0	0
Final Stored	0	0
Continuity Error (%)	0.026	

Time-Step Critical Elements
Link CO9 (1.12%)

Highest Flow Instability Indexes
Link N1 (1)
Link C1 (1)

Routing Time Step Summary
Minimum Time Step : 0.09 sec
Average Time Step : 1.00 sec
Maximum Time Step : 1.00 sec
Percent in Steady State : 0.00
Average Iterations per Step : 2.00
Percent Not Converging : 0.00

Subcatchment Runoff Summary

Subcatchment	Total Precip mm	Total Runon mm	Total Infil mm	Total Runoff mm	Total Runoff 10^6	Peak Runoff ltr	Runoff Coeff CMS
Apron1	25	96.91	0	121.91	0.01	0.01	1

Apron11	25	96.91	0	121.91	0.01	0.01	1
Apron12	25	96.91	0	121.91	0.01	0.01	1
Apron13	25	96.91	0	121.91	0.01	0.01	1
Apron14	25	96.73	0	121.73	0.03	0.01	1
Apron15	25	96.91	0	121.91	0.01	0.01	1
Apron16	25	96.73	0	121.73	0.03	0.01	1
Apron17	25	96.73	0	121.73	0.03	0.01	1
Apron18	25	96.73	0	121.73	0.03	0.01	1
Apron19	25	96.73	0	121.73	0.03	0.01	1
Apron2	25	96.91	0	121.91	0.01	0.01	1
Apron3	25	96.91	0	121.91	0.01	0.01	1
Apron4	25	96.73	0	121.73	0.03	0.01	1
Apron5	25	96.91	0	121.91	0.01	0.01	1
Apron6	25	96.73	0	121.73	0.03	0.01	1
Apron7	25	96.73	0	121.73	0.03	0.01	1
Apron8	25	96.73	0	121.73	0.03	0.01	1
Apron9	25	96.73	0	121.73	0.03	0.01	1
Driveway1	25	0	0	25	0.01	0.01	1
Driveway11	25	0	0	25	0.01	0.01	1
Driveway12	25	0	0	25	0.01	0.01	1
Driveway13	25	0	0	25	0.01	0.01	1
Driveway14	25	0	0	25	0.02	0.01	1
Driveway15	25	0	0	25	0.01	0.01	1
Driveway16	25	0	0	25	0.02	0.01	1
Driveway17	25	0	0	25	0.02	0.01	1
Driveway18	25	0	0	25	0.02	0.01	1
Driveway19	25	0	0	25	0.02	0.01	1
Driveway2	25	0	0	25	0.01	0.01	1
Driveway3	25	0	0	25	0.01	0.01	1
Driveway4	25	0	0	25	0.02	0.01	1
Driveway5	25	0	0	25	0.01	0.01	1
Driveway6	25	0	0	25	0.02	0.01	1
Driveway7	25	0	0	25	0.02	0.01	1
Driveway8	25	0	0	25	0.02	0.01	1
Driveway9	25	0	0	25	0.02	0.01	1
Half_street1	25	84.1	0	109.1	0.04	0.02	1
Half_street11	25	83.81	0	108.81	0.04	0.02	1
Half_street12	25	83.81	0	108.81	0.04	0.02	1
Half_Street13	25	83.81	0	108.81	0.04	0.02	1
Half_street14	25	83.96	0	108.95	0.07	0.03	1
Half_street15	25	83.81	0	108.81	0.04	0.02	1
Half_street16	25	83.73	0	108.71	0.07	0.03	1
Half_street17	25	83.73	0	108.72	0.07	0.03	1
Half_street18	25	83.73	0	108.72	0.07	0.03	1
Half_street19	25	83.73	0	108.72	0.07	0.03	1
Half_street2	25	83.81	0	108.81	0.04	0.02	1
Half_Street3	25	83.81	0	108.81	0.04	0.02	1
Half_street4	25	83.73	0	108.72	0.07	0.03	1

Half_street5	25	83.81	0	108.81	0.04	0.02	1
Half_street6	25	83.73	0	108.71	0.07	0.03	1
Half_street7	25	78.08	0	103.07	0.07	0.03	1
Half_street8	25	83.73	0	108.72	0.07	0.03	1
Half_street9	25	83.73	0	108.72	0.07	0.03	1
House&Garage1	25	0	0	25	0.02	0.01	1
House&Garage11	25	0	0	25	0.02	0.01	1
House&Garage12	25	0	0	25	0.02	0.01	1
House&Garage13	25	0	0	25	0.02	0.01	1
House&Garage14	25	0	0	25	0.04	0.02	1
House&Garage15	25	0	0	25	0.02	0.01	1
House&Garage16	25	0	0	25	0.04	0.02	1
House&Garage17	25	0	0	25	0.04	0.02	1
House&Garage18	25	0	0	25	0.04	0.02	1
House&Garage19	25	0	0	25	0.04	0.02	1
House&Garage2	25	0	0	25	0.02	0.01	1
House&Garage3	25	0	0	25	0.02	0.01	1
House&Garage4	25	0	0	25	0.04	0.02	1
House&Garage5	25	0	0	25	0.02	0.01	1
House&Garage6	25	0	0	25	0.04	0.02	1
House&Garage7	25	0	0	25	0.04	0.02	1
House&Garage8	25	0	0	25	0.04	0.02	1
House&Garage9	25	0	0	25	0.04	0.02	1
Sidewalk1	25	89.61	0	114.61	0.01	0.01	1
Sidewalk11	25	93.06	0	118.05	0.01	0.01	1
Sidewalk12	25	93.06	0	118.05	0.01	0.01	1
Sidewalk13	25	93.06	0	118.05	0.01	0.01	1
Sidewalk14	25	93.7	0	118.7	0.02	0.01	1
Sidewalk15	25	93.06	0	118.05	0.01	0.01	1
Sidewalk16	25	92.9	0	117.9	0.02	0.01	1
Sidewalk17	25	92.9	0	117.9	0.02	0.01	1
Sidewalk18	25	92.9	0	117.9	0.02	0.01	1
Sidewalk19	25	92.9	0	117.9	0.02	0.01	1
Sidewalk2	25	93.06	0	118.05	0.01	0.01	1
Sidewalk3	25	93.06	0	118.05	0.01	0.01	1
Sidewalk4	25	92.9	0	117.9	0.02	0.01	1
Sidewalk5	25	93.06	0	118.05	0.01	0.01	1
Sidewalk6	25	92.9	0	117.9	0.02	0.01	1
Sidewalk7	25	92.9	0	117.9	0.02	0.01	1
Sidewalk8	25	92.9	0	117.9	0.02	0.01	1
Sidewalk9	25	92.9	0	117.9	0.02	0.01	1
SR1	25	0	0	24.99	0.02	0.01	1
SR2	25	0	0	24.99	0.02	0.01	1
SR3	25	0	0	24.99	0.02	0.01	1
SR4	25	0	0	24.99	0.02	0.01	1
SR5	25	0	0	24.99	0.02	0.01	1
Tree_lawn1	25	28.79	20.6	33.15	0.01	0.01	0.616
Tree_lawn11	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn12	25	28.55	20.6	32.93	0.01	0.01	0.615

Tree_lawn13	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn14	25	28.98	20.6	33.34	0.03	0.02	0.618
Tree_lawn15	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn16	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn17	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn18	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn19	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn2	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn3	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn4	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn5	25	28.55	20.6	32.93	0.01	0.01	0.615
Tree_lawn6	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn7	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn8	25	28.78	20.6	33.16	0.03	0.02	0.617
Tree_lawn9	25	28.78	20.6	33.16	0.03	0.02	0.617
Yard1	25	0	20.1	4.89	0.01	0.01	0.196
Yard11	25	0	20.1	4.89	0.01	0.01	0.196
Yard12	25	0	20.1	4.89	0.01	0.01	0.196
Yard13	25	0	20.1	4.89	0.01	0.01	0.196
Yard14	25	0	20.1	4.87	0.02	0.01	0.195
Yard15	25	0	20.1	4.89	0.01	0.01	0.196
Yard16	25	0	20.1	4.89	0.02	0.01	0.196
Yard17	25	0	20.1	4.89	0.02	0.01	0.196
Yard18	25	0	20.1	4.89	0.02	0.01	0.196
Yard19	25	0	20.1	4.89	0.02	0.01	0.196
Yard2	25	0	20.1	4.89	0.01	0.01	0.196
Yard3	25	0	20.1	4.89	0.01	0.01	0.196
Yard4	25	0	20.1	4.89	0.02	0.01	0.196
Yard5	25	0	20.1	4.89	0.01	0.01	0.196
Yard6	25	0	20.1	4.89	0.02	0.01	0.196
Yard7	25	0	20.1	4.89	0.02	0.01	0.196
Yard8	25	0	20.1	4.89	0.02	0.01	0.196
Yard9	25	0	20.1	4.89	0.02	0.01	0.196

Node Depth Summary

Node	Type	Average Depth Meters	Max Depth Meters	Max HGL Meters	Timeof Max Occurrence days	hr:min	Reported Depth Meters
1-Jun	JUNCTION	0	0.1	332	0	0:25	0.1
2-Jun	JUNCTION	0.01	0.17	328	0	0:30	0.17
3-Jun	JUNCTION	0.01	0.23	327	0	0:30	0.23
4-Jun	JUNCTION	0.01	0.26	325	0	0:30	0.26
5-Jun	JUNCTION	0.02	0.38	324	0	0:30	0.38
6-Jun	JUNCTION	0.02	0.42	324	0	0:35	0.42
7-Jun	JUNCTION	0.01	0.3	323	0	0:35	0.3
8-Jun	JUNCTION	0.02	0.37	320	0	0:35	0.37
9-Jun	JUNCTION	0.01	0.19	317	0	0:40	0.19
J1	JUNCTION	0	0.06	334	0	0:40	0.06
J10	JUNCTION	0	0.12	326	0	0:46	0.12
J11	JUNCTION	0.01	0.1	326	0	0:46	0.1
J12	JUNCTION	0	0.1	326	0	0:47	0.1

J13	JUNCTION	0.01	0.1	325	0	0:46	0.1
J14	JUNCTION	0	0.1	325	0	0:48	0.1
J15	JUNCTION	0.01	0.11	322	0	0:47	0.11
J16	JUNCTION	0	0.11	322	0	0:48	0.11
J17	JUNCTION	0	0.07	319	0	0:46	0.07
J2	JUNCTION	0	0.05	334	0	0:40	0.05
J3	JUNCTION	0	0.07	330	0	0:40	0.07
J4	JUNCTION	0	0.06	330	0	0:40	0.06
J5	JUNCTION	0	0.07	329	0	0:40	0.07
J6	JUNCTION	0	0.07	329	0	0:41	0.07
J7	JUNCTION	0.01	0.09	327	0	0:41	0.09
J8	JUNCTION	0	0.09	327	0	0:42	0.09
J9	JUNCTION	0.01	0.1	326	0	0:45	0.1
U1	JUNCTION	0	0.06	334	0	0:40	0.06
U10	JUNCTION	0	0.11	326	0	0:44	0.11
U11	JUNCTION	0.01	0.1	326	0	0:45	0.1
U12	JUNCTION	0	0.11	326	0	0:45	0.11
U13	JUNCTION	0.01	0.1	325	0	0:45	0.1
U14	JUNCTION	0	0.1	325	0	0:46	0.1
U15	JUNCTION	0.01	0.11	322	0	0:46	0.11
U16	JUNCTION	0	0.11	322	0	0:47	0.11
U17	JUNCTION	0	0.07	319	0	0:46	0.07
U2	JUNCTION	0	0.05	334	0	0:40	0.05
U3	JUNCTION	0	0.07	330	0	0:40	0.07
U4	JUNCTION	0	0.06	330	0	0:40	0.06
U5	JUNCTION	0	0.07	329	0	0:40	0.07
U6	JUNCTION	0	0.07	329	0	0:41	0.07
U7	JUNCTION	0.01	0.09	327	0	0:41	0.09
U8	JUNCTION	0	0.09	327	0	0:42	0.09
U9	JUNCTION	0.01	0.1	326	0	0:43	0.1
OUT1	OUTFALL	0.01	0.19	314	0	0:40	0.19

Node Inflow Summary

Node	Type	Maximum Lateral Inflow CMS	Maximum Total Inflow CMS	Total of Volume hr:min	Flow Max Volume 10^6	Inflow Error ltr	Inflow 10^6
1-Jun	JUNCTION	0.023	0.04	0:25	0.0415	0.0922	-0.001
2-Jun	JUNCTION	0.031	0.09	0:30	0.0577	0.214	-0.003
3-Jun	JUNCTION	0.023	0.14	0:30	0.0415	0.323	-0.006
4-Jun	JUNCTION	0.044	0.2	0:30	0.08	0.493	-0.003
5-Jun	JUNCTION	0.023	0.25	0:30	0.0415	0.625	-0.077
6-Jun	JUNCTION	0.061	0.32	0:30	0.112	0.84	0.055
7-Jun	JUNCTION	0.061	0.4	0:35	0.112	1.05	-0.01
8-Jun	JUNCTION	0.044	0.46	0:35	0.08	1.23	0.021
9-Jun	JUNCTION	0.044	0.62	0:39	0.08	1.64	-0.009
J1	JUNCTION	0.016	0.02	0:39	0.0355	0.0355	0.025
J10	JUNCTION	0	0.04	0:42	0	0.0758	-0.102
J11	JUNCTION	0.03	0.05	0:44	0.0707	0.1	0.13
J12	JUNCTION	0	0.05	0:46	0	0.1	0.342
J13	JUNCTION	0.032	0.06	0:45	0.0719	0.121	-0.235
J14	JUNCTION	0	0.06	0:46	0	0.121	0.151
J15	JUNCTION	0.031	0.07	0:45	0.0707	0.142	-0.094
J16	JUNCTION	0	0.07	0:47	0	0.142	0.152
J17	JUNCTION	0.031	0.08	0:45	0.0707	0.161	-0.133
J2	JUNCTION	0	0.02	0:40	0	0.0355	-0.03

J3	JUNCTION	0.016	0.02	0:39	0.0354	0.0455	0.08
J4	JUNCTION	0	0.02	0:40	0	0.0454	-0.018
J5	JUNCTION	0.016	0.03	0:39	0.0354	0.049	0.071
J6	JUNCTION	0	0.03	0:40	0	0.049	-0.182
J7	JUNCTION	0.031	0.04	0:40	0.0707	0.0858	0.17
J8	JUNCTION	0	0.04	0:41	0	0.0856	-0.015
J9	JUNCTION	0.016	0.04	0:41	0.0354	0.0758	0.052
U1	JUNCTION	0.016	0.02	0:39	0.0354	0.0354	0.026
U10	JUNCTION	0	0.04	0:42	0	0.0759	-0.057
U11	JUNCTION	0.03	0.05	0:43	0.0707	0.103	0.068
U12	JUNCTION	0	0.05	0:44	0	0.103	0.234
U13	JUNCTION	0.031	0.07	0:44	0.0707	0.122	-0.149
U14	JUNCTION	0	0.07	0:45	0	0.123	0.114
U15	JUNCTION	0.031	0.08	0:45	0.0707	0.145	-0.063
U16	JUNCTION	0	0.08	0:46	0	0.145	0.139
U17	JUNCTION	0.031	0.09	0:45	0.0707	0.164	-0.121
U2	JUNCTION	0	0.02	0:40	0	0.0354	-0.03
U3	JUNCTION	0.016	0.02	0:39	0.0354	0.0454	0.08
U4	JUNCTION	0	0.02	0:40	0	0.0454	-0.018
U5	JUNCTION	0.016	0.03	0:39	0.0354	0.049	0.071
U6	JUNCTION	0	0.02	0:40	0	0.0489	-0.185
U7	JUNCTION	0.031	0.04	0:40	0.0708	0.0859	0.171
U8	JUNCTION	0	0.04	0:41	0	0.0857	0.041
U9	JUNCTION	0.016	0.04	0:41	0.0354	0.0758	-0.009
OUT1	OUTFALL	0	0.62	0:40	0	1.64	0

Node Surcharge Summary
No nodes were surcharged.

Node Flooding Summary
No nodes were flooded.

Outfall Loading Summary

Outfall Node	Flow Freq Pcnt	Avg Flow CMS	Max Flow CMS	Total Volume 10^6
O1	39.95	0.041	0.622	1.638
System	39.95	0.041	0.622	1.638

Link Flow Summary

Link	Type	Maximum |Flow| CMS	Timeof Occurence hr:min	Max |Veloc| m/sec	Max/ Full Flow	Max/ Full Depth
C1	CHANNEL	0.016	0:40	0.65	0	0.06
C10	CHANNEL	0.021	0:46	0.29	0	0.1
C11	CHANNEL	0.05	0:46	0.68	0	0.1
C12	CHANNEL	0.032	0:47	0.49	0	0.09
C13	CHANNEL	0.061	0:46	0.81	0	0.1
C14	CHANNEL	0.044	0:48	0.67	0	0.09
C15	CHANNEL	0.072	0:47	0.8	0.01	0.11
C16	CHANNEL	0.054	0:48	1.14	0	0.08
C2	CHANNEL	0.006	0:40	0.31	0	0.05
C3	CHANNEL	0.022	0:40	0.66	0	0.07
C4	CHANNEL	0.009	0:40	0.35	0	0.06

C5	CHANNEL	0.025	0:40	0.66	0	0.07
C6	CHANNEL	0.011	0:41	0.29	0	0.07
C7	CHANNEL	0.041	0:41	0.71	0	0.09
C8	CHANNEL	0.026	0:42	0.5	0	0.08
C9	CHANNEL	0.04	0:42	0.65	0	0.11
CO1	CONDUIT	0.039	0:25	1.86	0.24	0.33
CO2	CONDUIT	0.09	0:30	1.57	0.31	0.38
CO3	CONDUIT	0.134	0:30	1.44	0.39	0.43
CO4	CONDUIT	0.198	0:30	1.7	0.37	0.42
CO5	CONDUIT	0.244	0:30	1	0.51	0.53
CO6	CONDUIT	0.32	0:35	1.5	0.56	0.47
CO7	CONDUIT	0.397	0:35	2.05	0.33	0.44
CO8	CONDUIT	0.461	0:35	3.06	0.4	0.37
CO9	CONDUIT	0.622	0:40	6.99	0.14	0.25
N1	CHANNEL	0.016	0:40	0.65	0	0.06
N10	CHANNEL	0.023	0:44	0.34	0	0.09
N11	CHANNEL	0.053	0:44	0.68	0	0.1
N12	CHANNEL	0.035	0:45	0.51	0	0.1
N13	CHANNEL	0.065	0:45	0.82	0	0.1
N14	CHANNEL	0.048	0:46	0.69	0	0.1
N15	CHANNEL	0.076	0:46	0.82	0.01	0.11
N16	CHANNEL	0.059	0:47	1.16	0	0.08
N2	CHANNEL	0.006	0:40	0.31	0	0.05
N3	CHANNEL	0.022	0:40	0.66	0	0.07
N4	CHANNEL	0.009	0:40	0.35	0	0.06
N5	CHANNEL	0.024	0:40	0.66	0	0.07
N6	CHANNEL	0.011	0:41	0.29	0	0.07
N7	CHANNEL	0.041	0:41	0.71	0	0.09
N8	CHANNEL	0.026	0:42	0.52	0	0.08
N9	CHANNEL	0.041	0:42	0.61	0	0.1
C17	CONDUIT	0.068	0:46	1.35	0.02	0.17
C18	CONDUIT	0.073	0:46	1.42	0.02	0.17
O1	ORIFICE	0.01	0:40			
O2	ORIFICE	0.013	0:40			
O3	ORIFICE	0.014	0:41			
O4	ORIFICE	0.015	0:42			
O5	ORIFICE	0.018	0:46			
O6	ORIFICE	0.017	0:47			
O7	ORIFICE	0.016	0:48			
O8	ORIFICE	0.017	0:48			
O9	ORIFICE	0.014	0:46			
R1	ORIFICE	0.01	0:40			
R2	ORIFICE	0.013	0:40			
R3	ORIFICE	0.014	0:41			
R4	ORIFICE	0.015	0:42			
R5	ORIFICE	0.017	0:44			
R6	ORIFICE	0.017	0:45			
R7	ORIFICE	0.017	0:46			
R8	ORIFICE	0.017	0:47			
R9	ORIFICE	0.014	0:46			

Flow Classification Summary

Conduit	Adjusted /Actual Length	Dry	Up Dry	Down Dry	Fraction of Time in Flow Class Sub Crit	Sup Crit	up Crit	Down Crit	Norm Ltd
C1	1	0	0	0	0.77	0.22	0	0	0.02
C10	1	0	0.96	0	0.03	0	0	0	0.99
C11	1	0	0	0	0.24	0.76	0	0	0.01
C12	1	0	0.96	0	0.04	0	0	0	0.99
C13	1	0	0	0	0.38	0.61	0	0	0.03
C14	1	0	0.96	0	0.04	0	0	0	0.99
C15	1	0	0	0	0.41	0.58	0	0	0.02
C16	1	0.11	0.85	0	0.01	0.03	0	0	0.96
C2	1	0	0.96	0	0.03	0	0	0	0.99
C3	1	0	0	0	0.69	0.31	0	0	0.02
C4	1	0	0.96	0	0.03	0	0	0	0.99
C5	1	0	0	0	0.64	0.35	0	0	0.02
C6	1	0	0.96	0	0.03	0	0	0	0.99
C7	1	0	0	0	0.33	0.67	0	0	0.03
C8	1	0	0.96	0	0.04	0	0	0	0.99
C9	1	0	0	0	0.64	0.35	0	0	0.01
CO1	1	0	0	0	0	0	0	1	0
CO2	1	0	0	0	0	0	0	1	0
CO3	1	0	0	0	0	0	0	1	0
CO4	1	0	0	0	0	0	0	1	0
CO5	1	0	0.05	0	0.95	0	0	0	0.97
CO6	1	0	0	0	1	0	0	0	0.11
CO7	1	0	0	0	0.92	0.08	0	0	0.84
CO8	1	0	0	0	0.68	0.31	0	0	0.19
CO9	1	0	0	0	0.23	0.77	0	0	0.03
N1	1	0	0	0	0.77	0.22	0	0	0.02
N10	1	0	0.96	0	0.03	0	0	0	0.99
N11	1	0	0	0	0.28	0.71	0	0	0.01
N12	1	0	0.96	0	0.04	0	0	0	0.99
N13	1	0	0	0	0.4	0.59	0	0	0.03
N14	1	0	0.96	0	0.04	0	0	0	0.99
N15	1	0	0	0	0.41	0.58	0	0	0.02
N16	1	0.11	0.85	0	0.01	0.03	0	0	0.96
N2	1	0	0.96	0	0.03	0	0	0	0.99
N3	1	0	0	0	0.69	0.31	0	0	0.02
N4	1	0	0.96	0	0.03	0	0	0	0.99
N5	1	0	0	0	0.64	0.35	0	0	0.02
N6	1	0	0.96	0	0.03	0	0	0	0.99
N7	1	0	0	0	0.33	0.67	0	0	0.03
N8	1	0	0.96	0	0.04	0	0	0	0.99
N9	1	0	0	0	0.64	0.36	0	0	0
C17	1	0	0.11	0	0.87	0.02	0	0	1
C18	1	0	0.11	0	0.87	0.02	0	0	1

Conduit Surcharge Summary

No conduits were surcharged